SUPERNOVAE AND NEUTRINOS

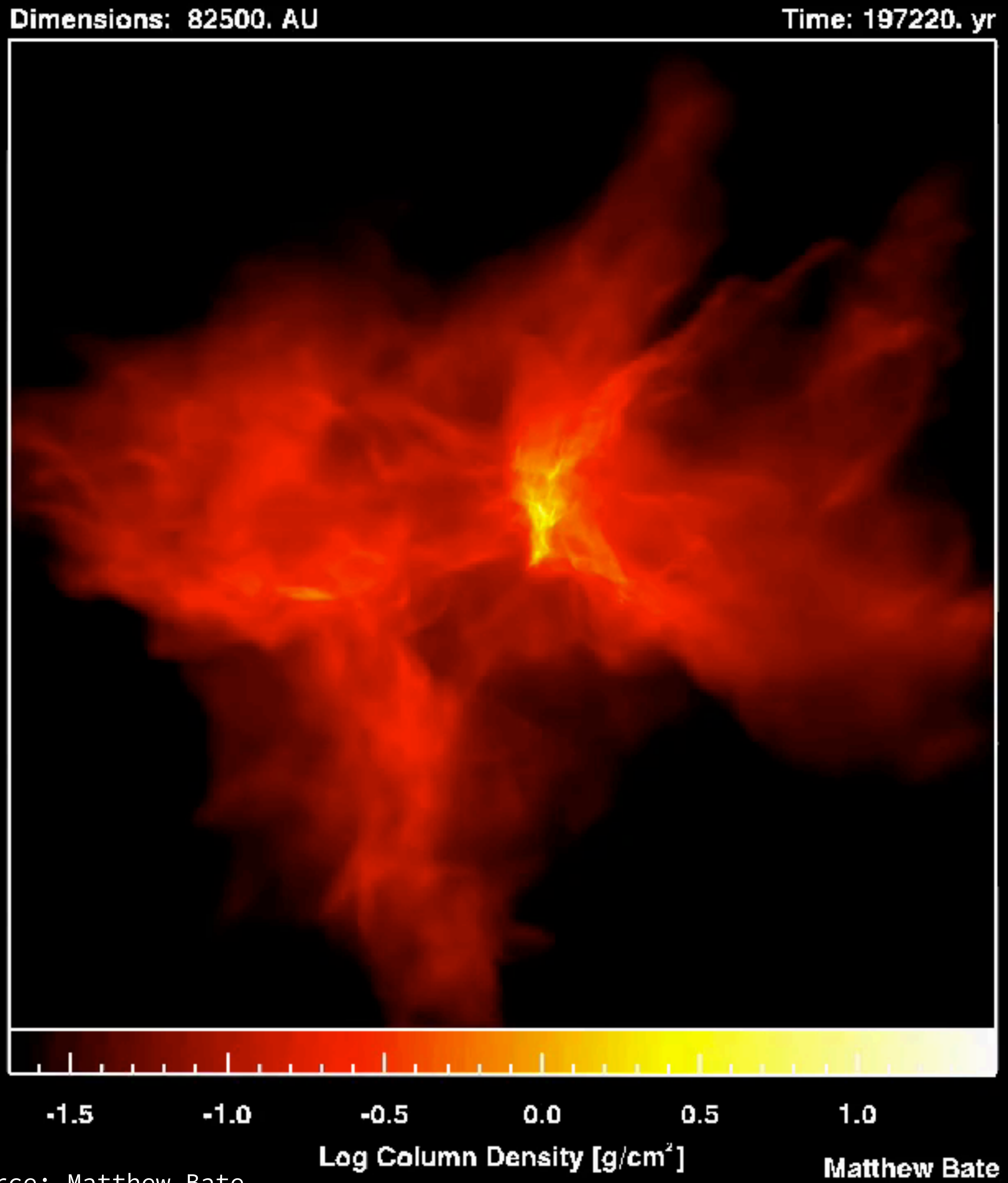
...where enormous explosions meet puny particles

JUSTIN VASEL

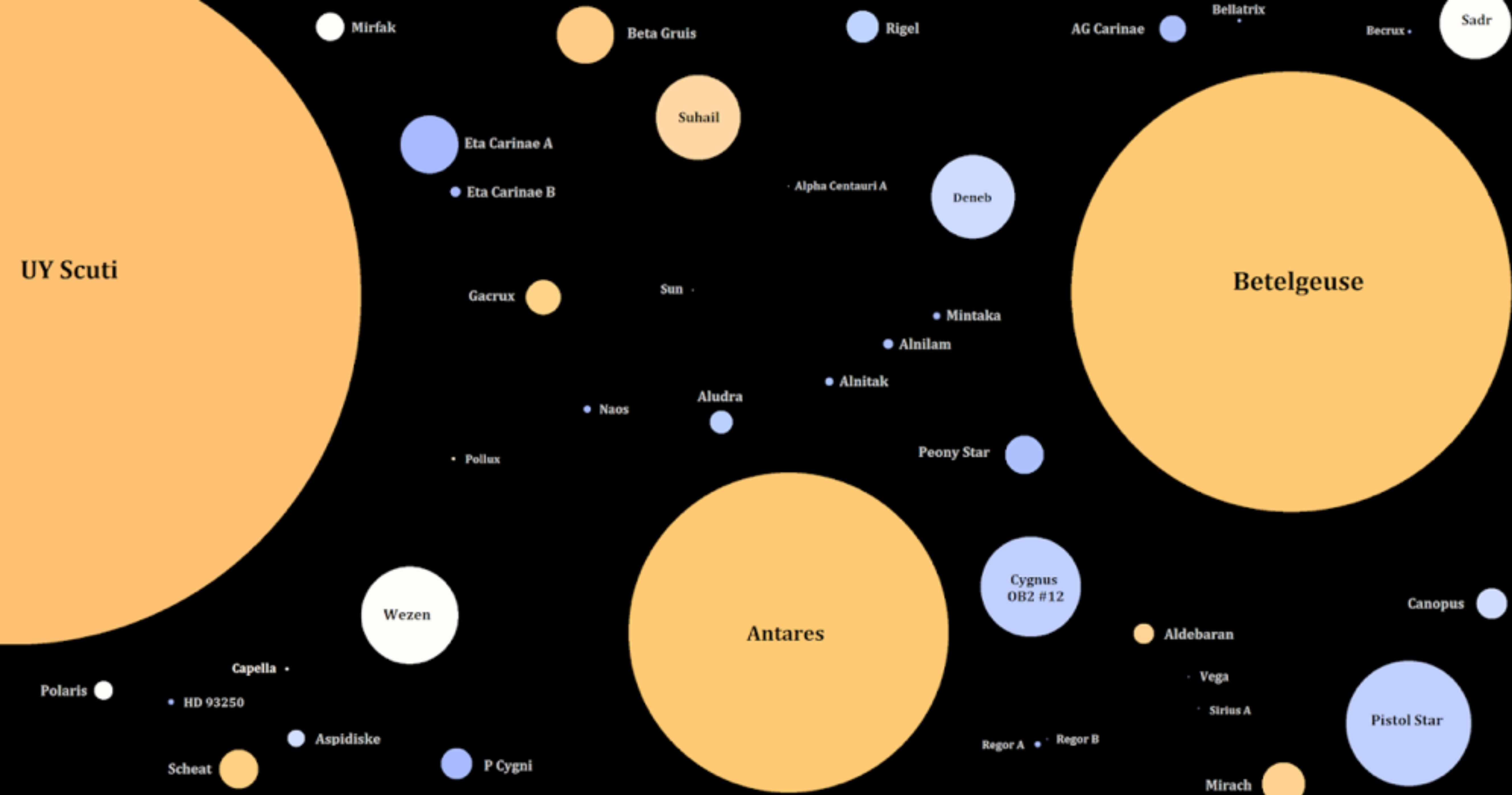
Ask a Scientist - Fermilab

8 January 2017

Source: NASA



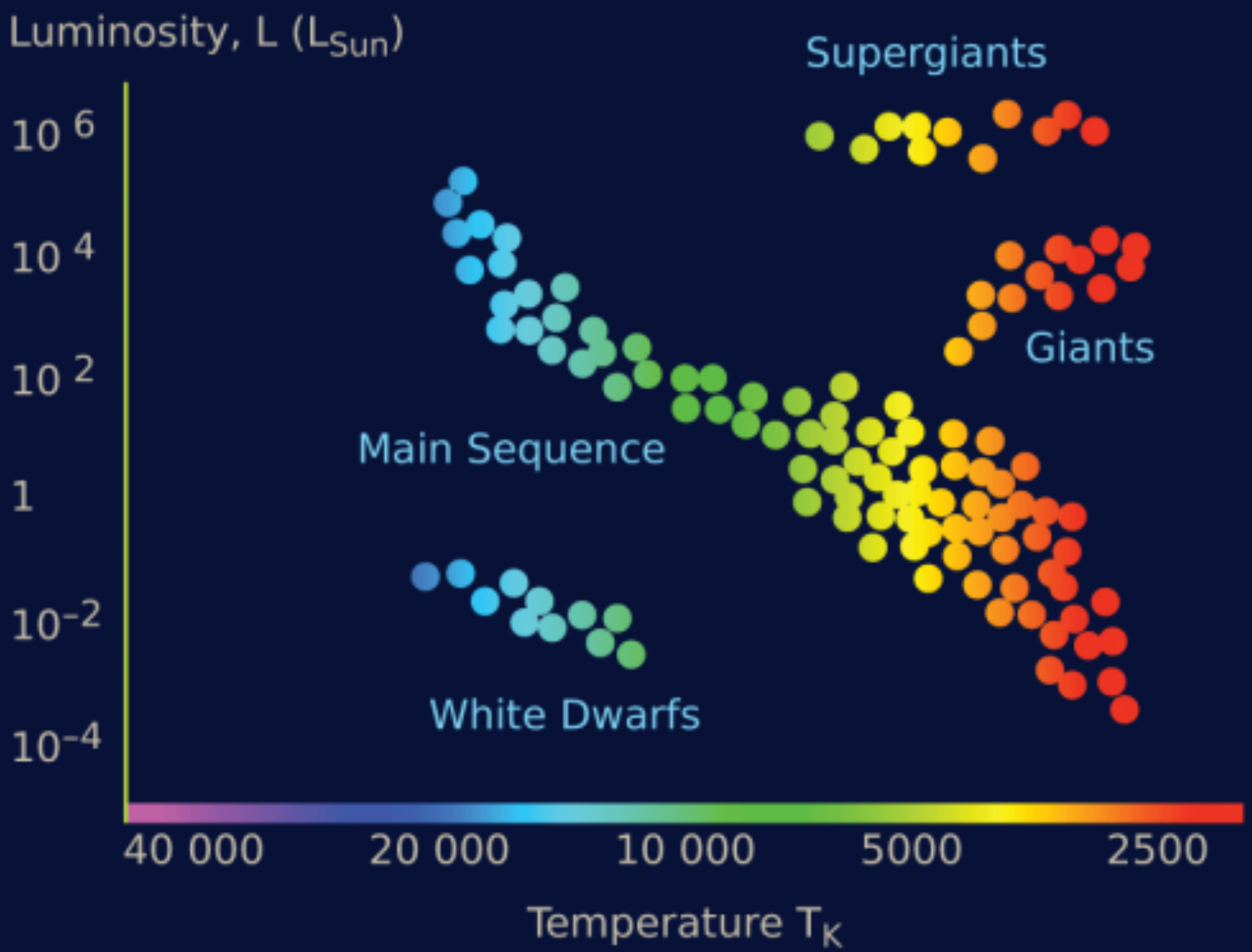
Source: Matthew Bate



Stars come in many sizes and colors.

They can live for a few million years, or billions of years.

Source: GiovanniMartin16, via Wikimedia Commons



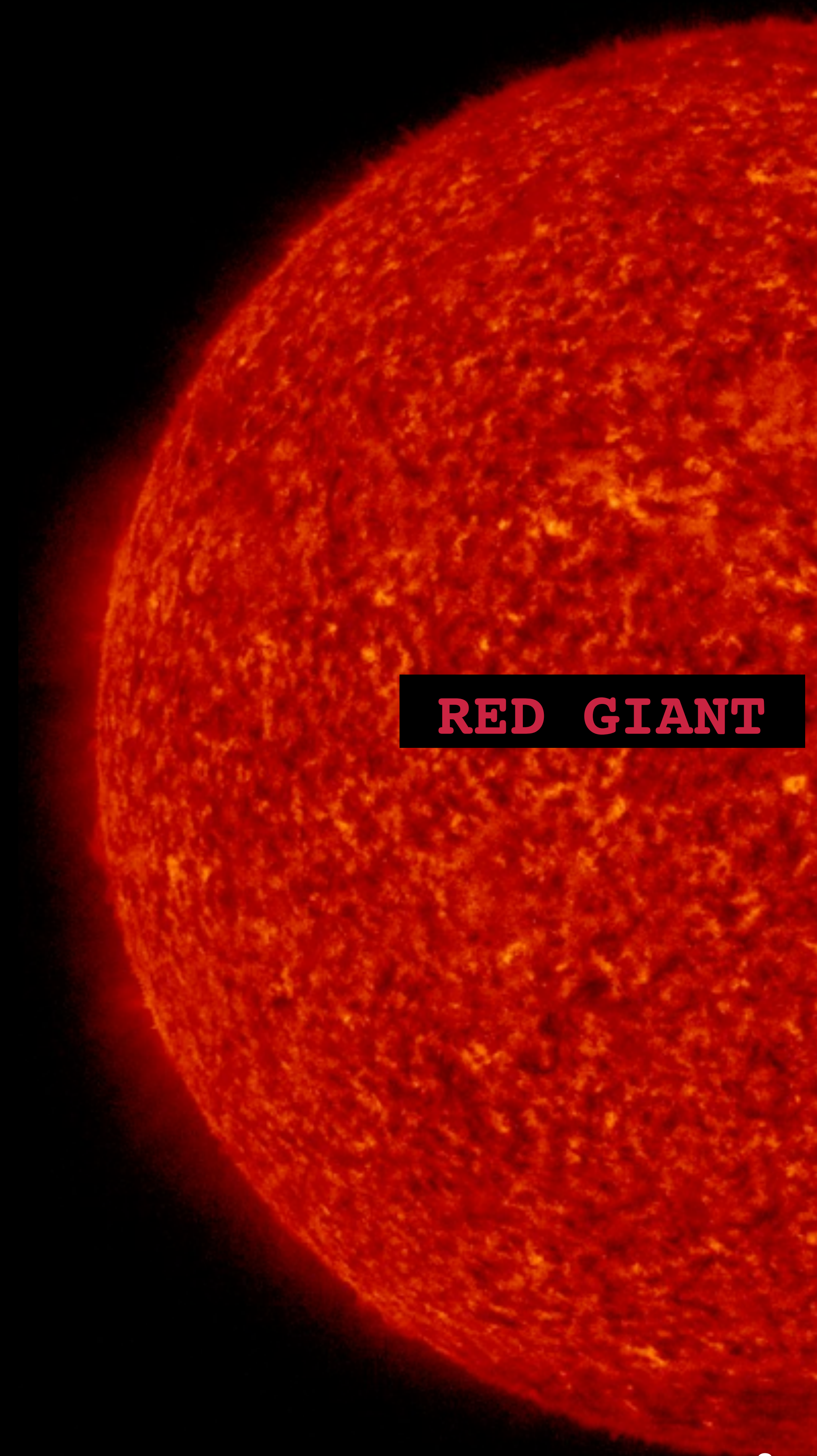
Luminosity, L (L_{Sun})
Supergiants
10^6
10^4
Giants
10^2
Main Sequence
1
10^{-2}
White Dwarfs
10^{-4}
40 000
20 000
10 000
5000
2500
Temperature T_K

Mid-sized stars

like THE SUN

Star runs low on
hydrogen fuel

Outer layers of
star swell up



RG phase only lasts for a short period.

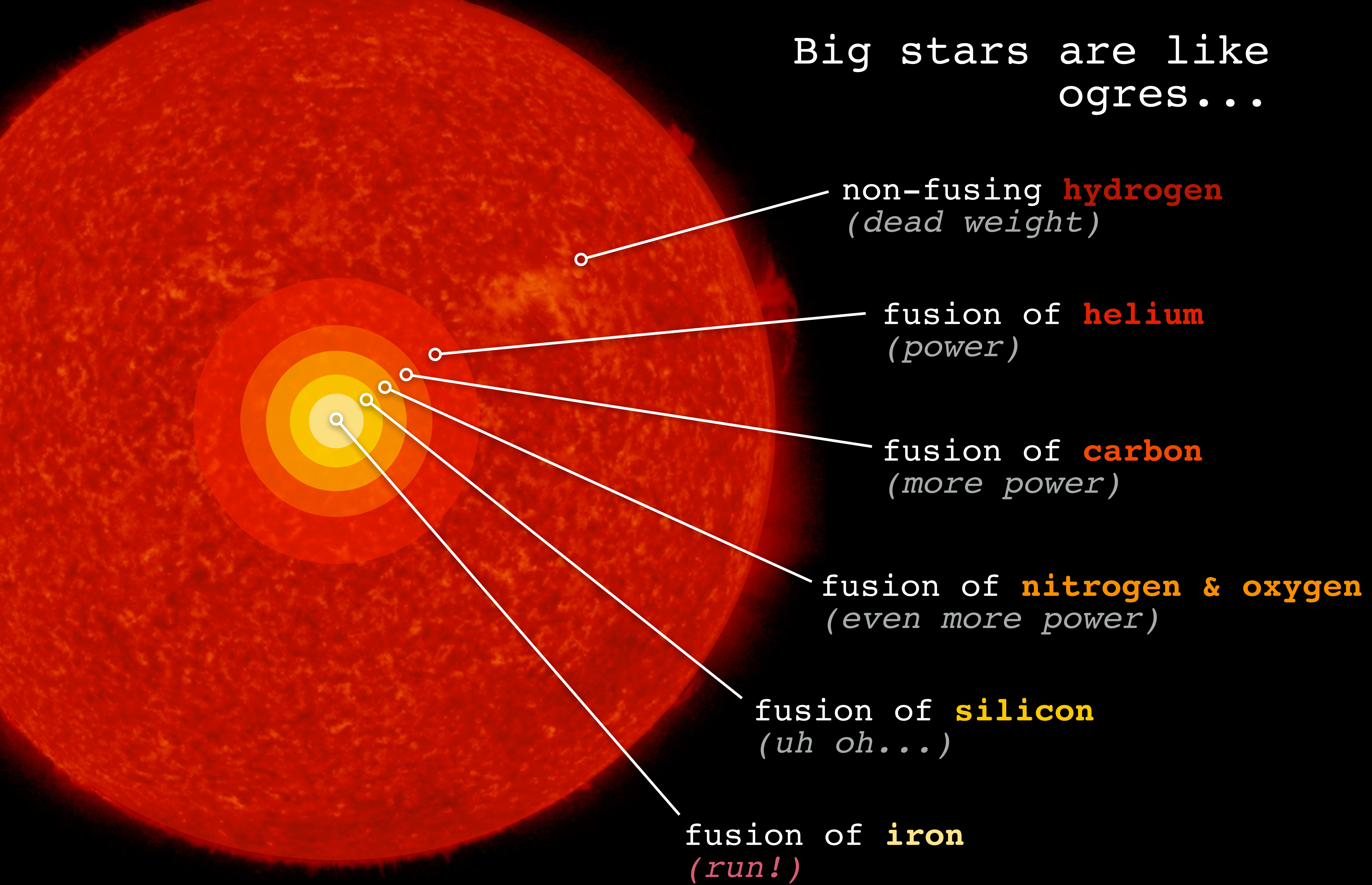
Variations in the last stages of burning cause the star to shrug off its outer layers

White dwarf

(hot ball of mostly carbon)

White dwarf cools over time, surrounded by the layers of gas it shed

Big stars are like ogres...

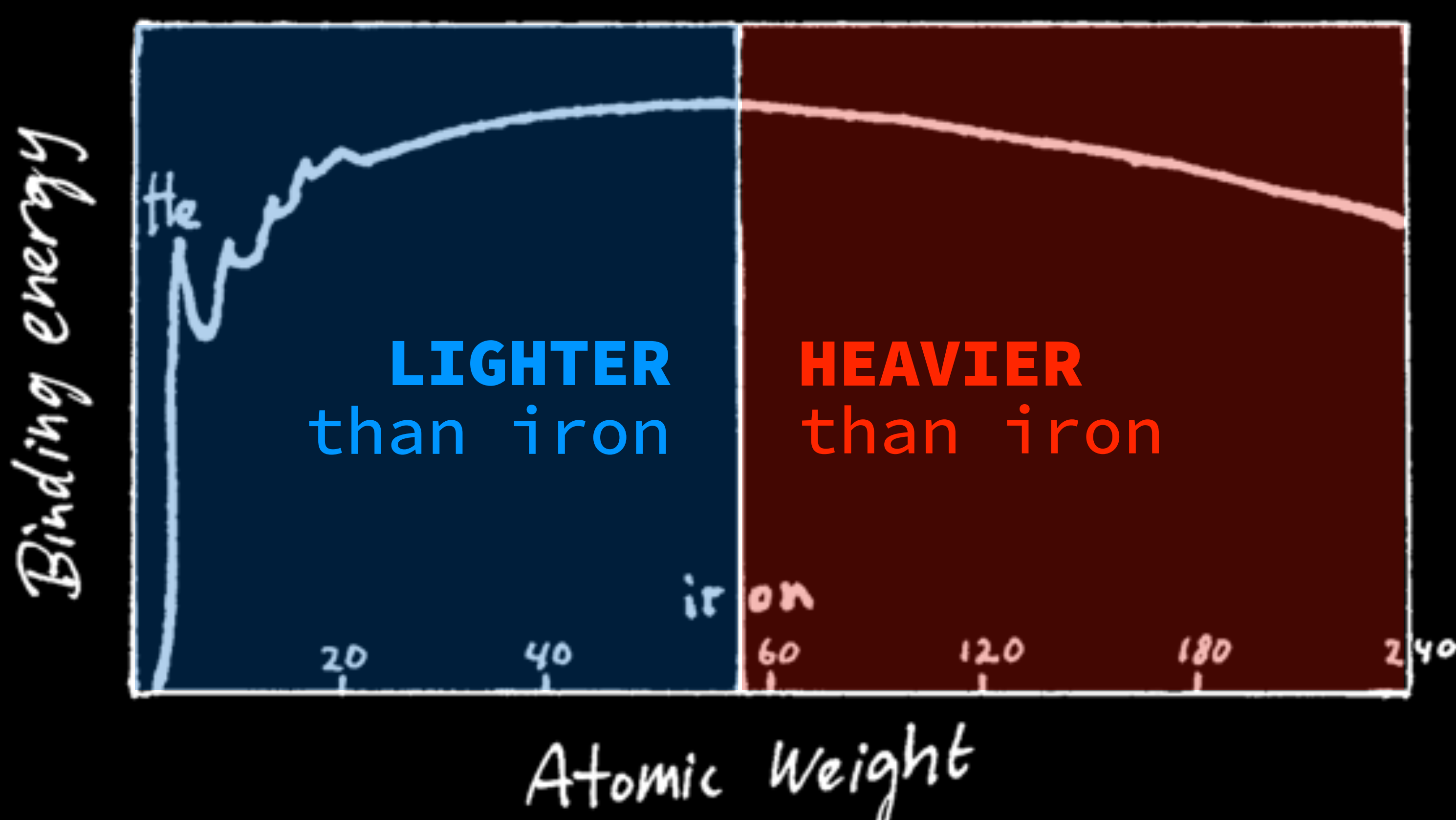


adapted from the figure:
http://www.dangthatscool.com/wp-content/uploads/2009/07/stardiagram3.jpg

Wait...what was that about iron?

Fusing elements lighter than iron releases energy (power!)

Fusing elements heavier than iron requires energy



Once **<u>iron</u>** is created in the core, there is no fuel left.

The core begins a **rapid collapse** under its own weight.

Core-collapse supernova

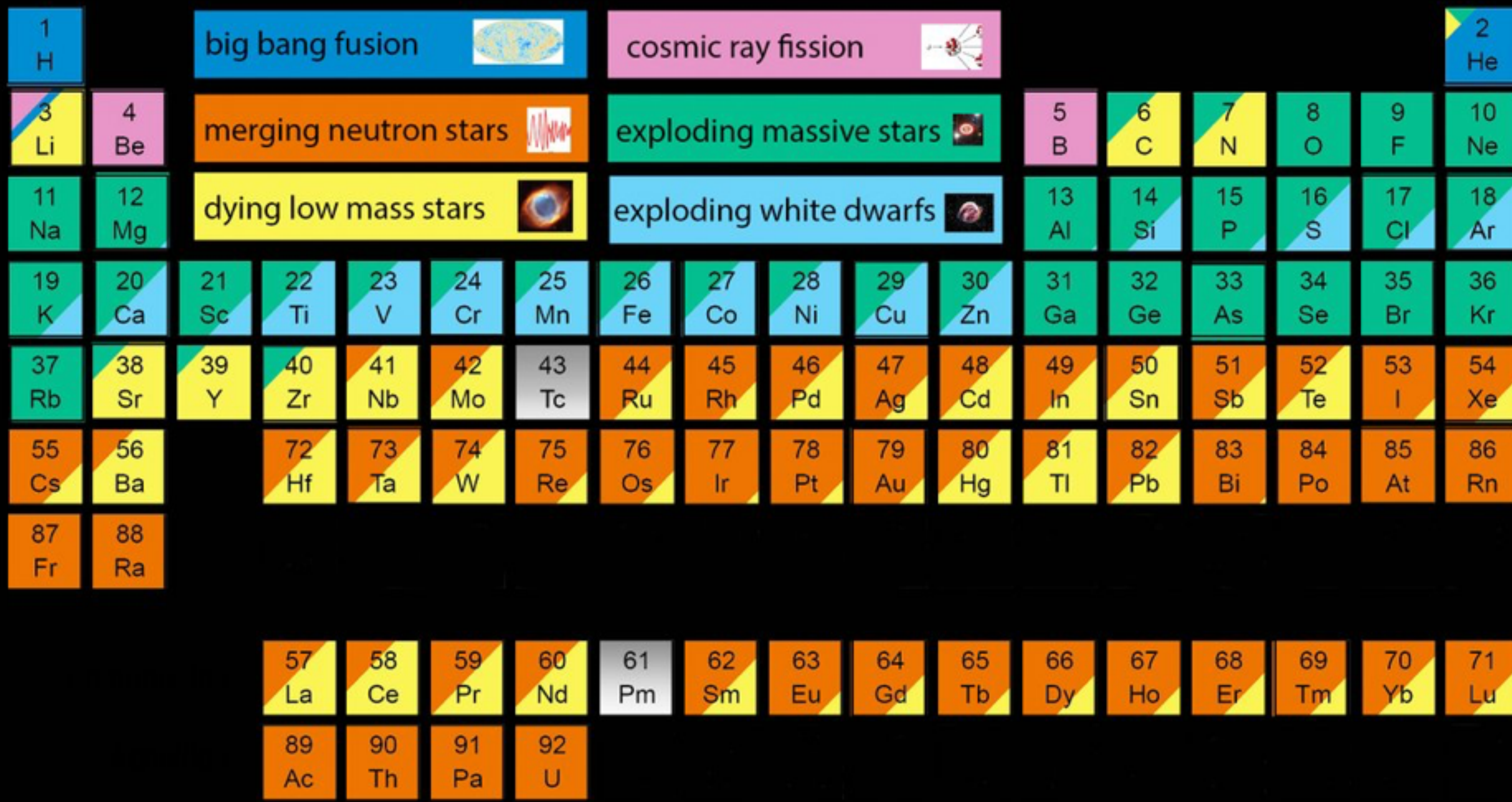
Gas and dust are ejected and strewn about

Outer layers of star are blown apart

Light from explosion can outshine galaxies.

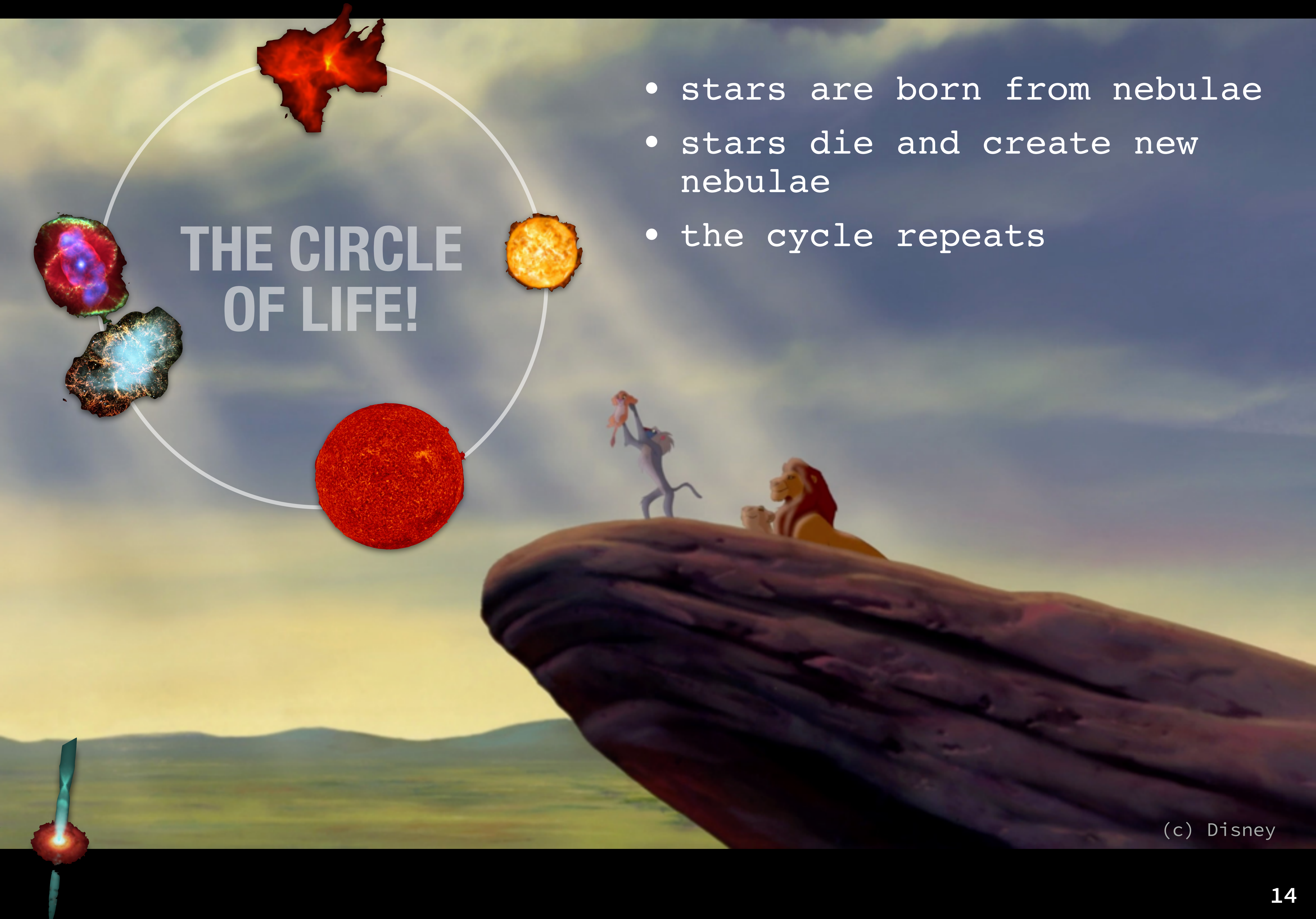
Don’t be around when this happens...

The cosmic ecosystem

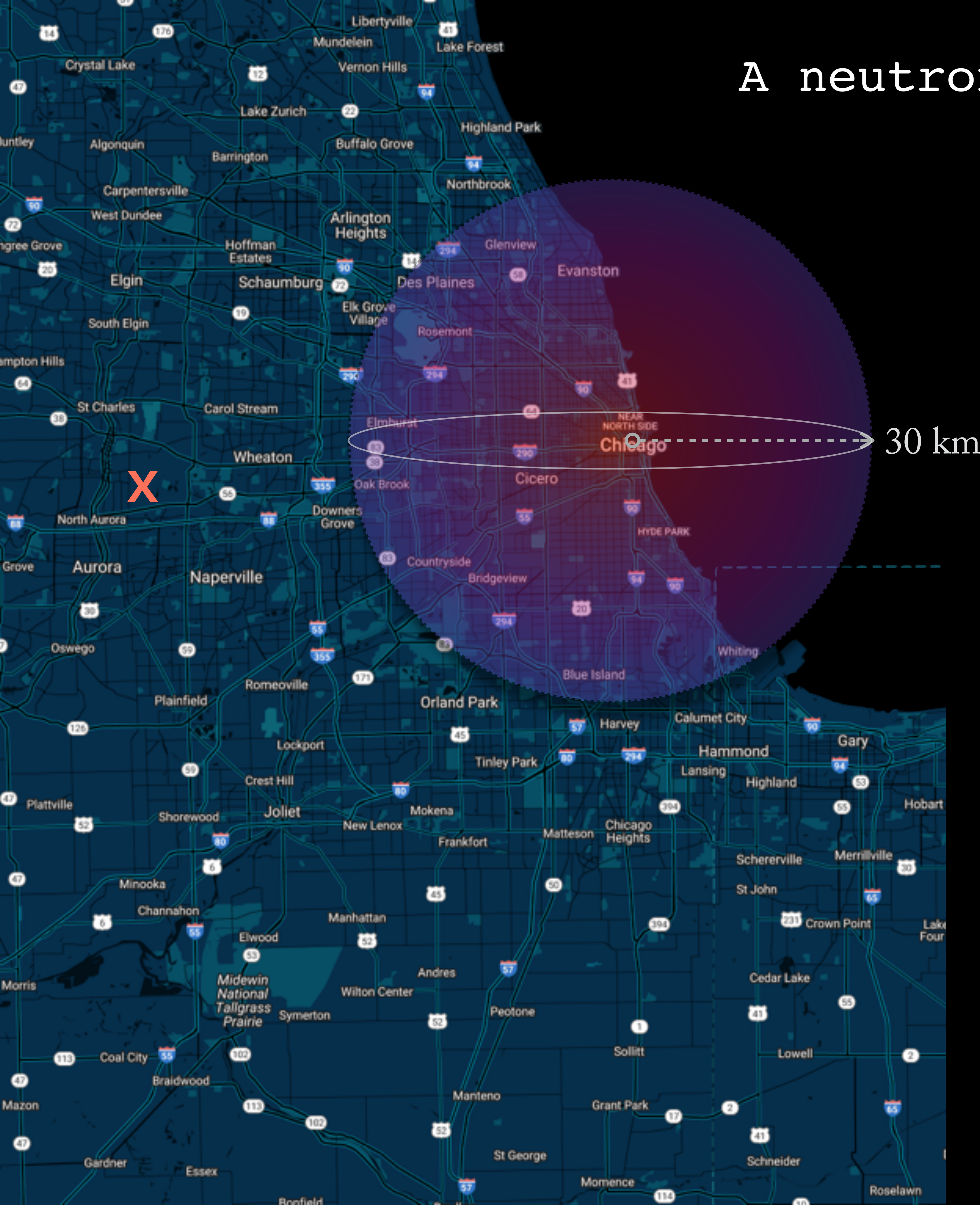


Source: Jennifer Johnson (@jajohnson51)

- stars are born from nebulae
- stars die and create new nebulae
- the cycle repeats



A neutron star over Chicago

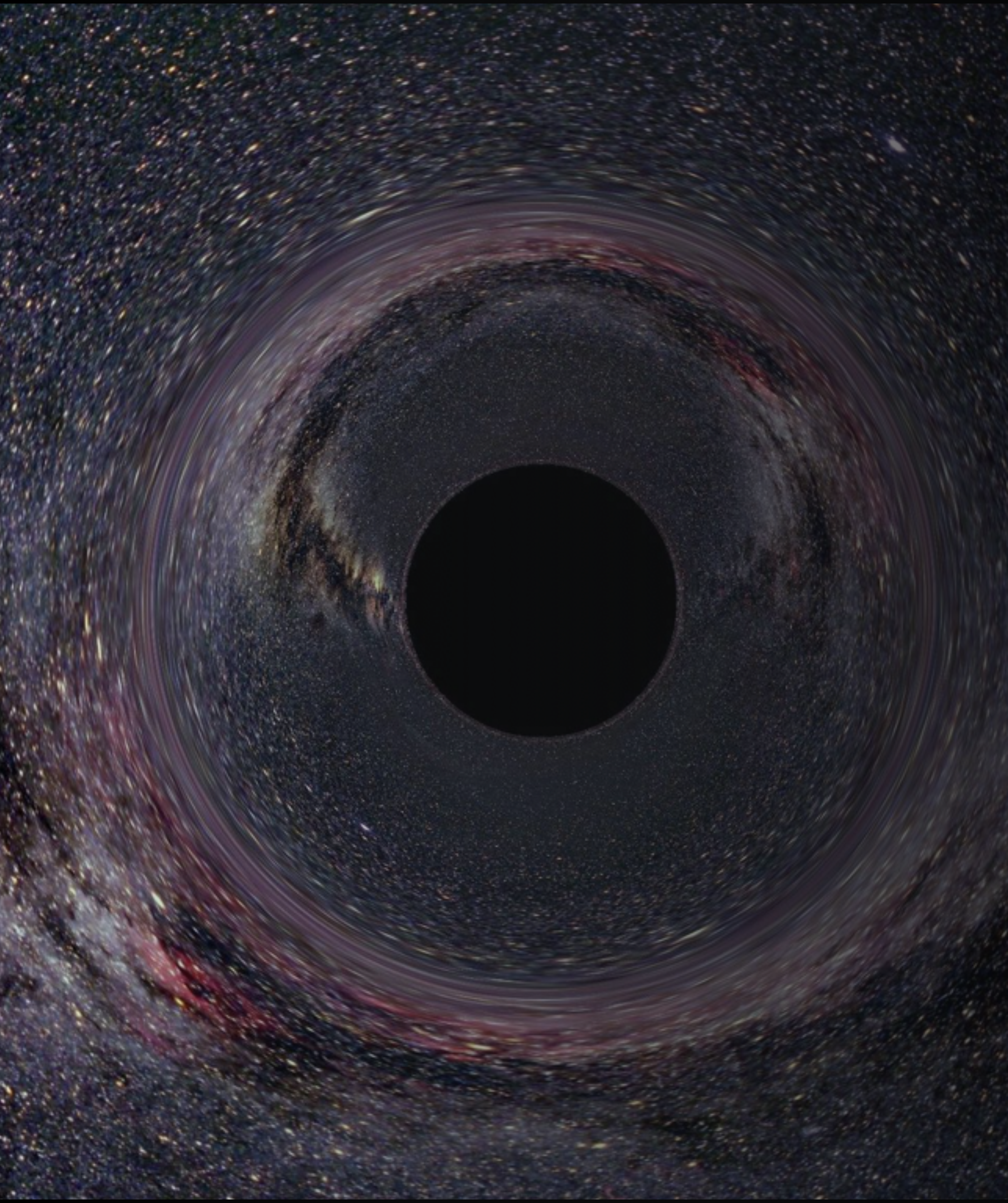


Hot, dense ball of neutrons left to cool for eternity

$1 - 3\ \mathrm{M}_{\odot}$ contained in a sphere 19 miles in radius

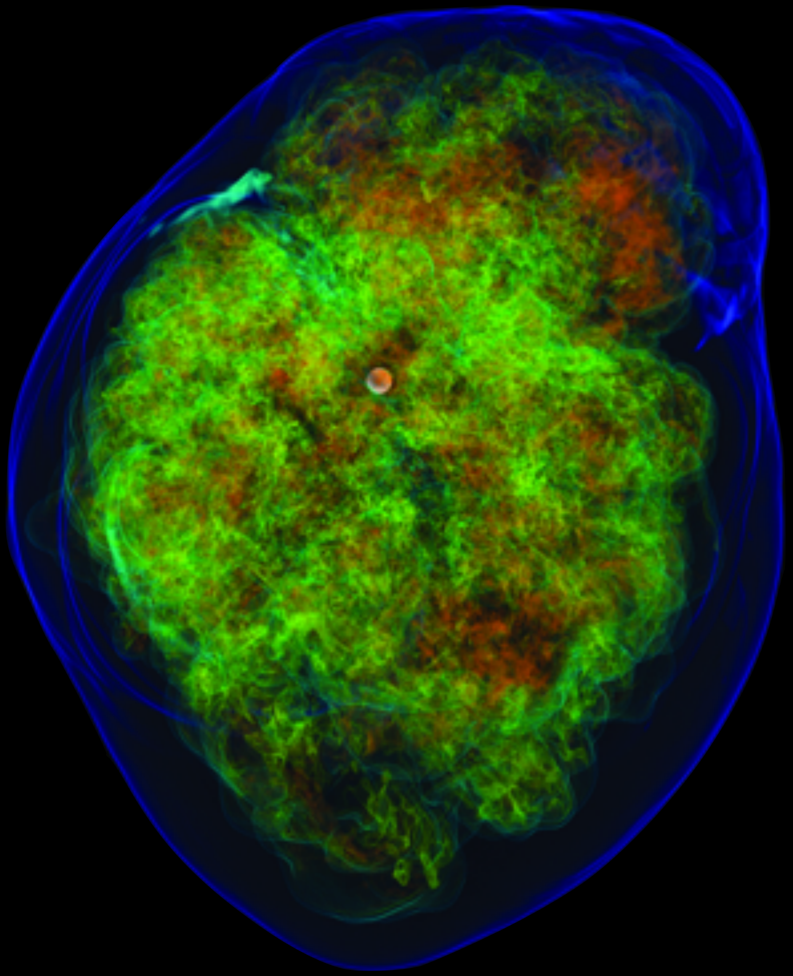
1 teaspoon would weigh 1 trillion pounds on Earth.

Black hole



If star is massive
enough (> 20 suns),
will collapse into
a black hole.

Simulations



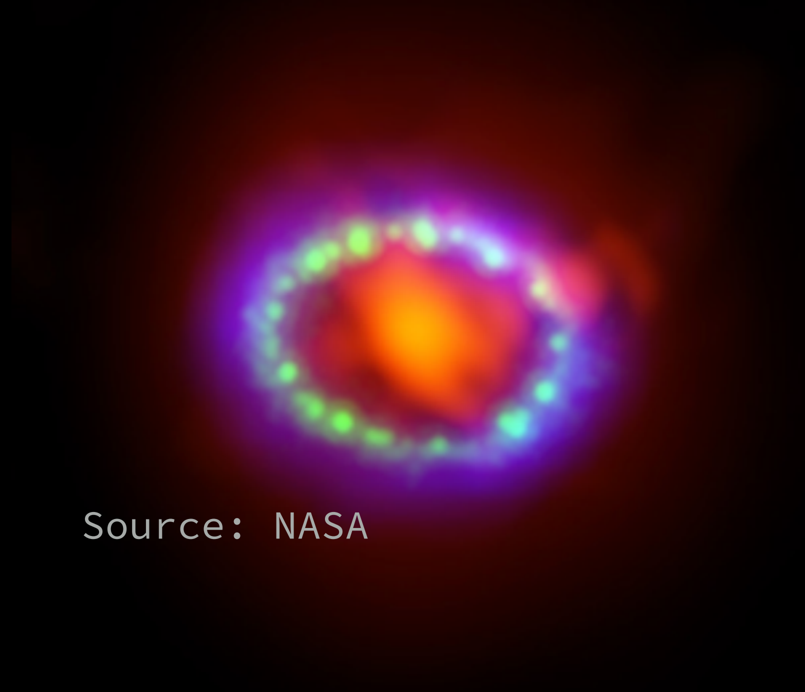
We have not seen many supernovae since dawn of telescopes; we rely on simulations.

Plug all of your physics equations into a computer program and let it run on a supercomputer.

Conundrum!

The star doesn't explode...

Neutrino production in supernovae

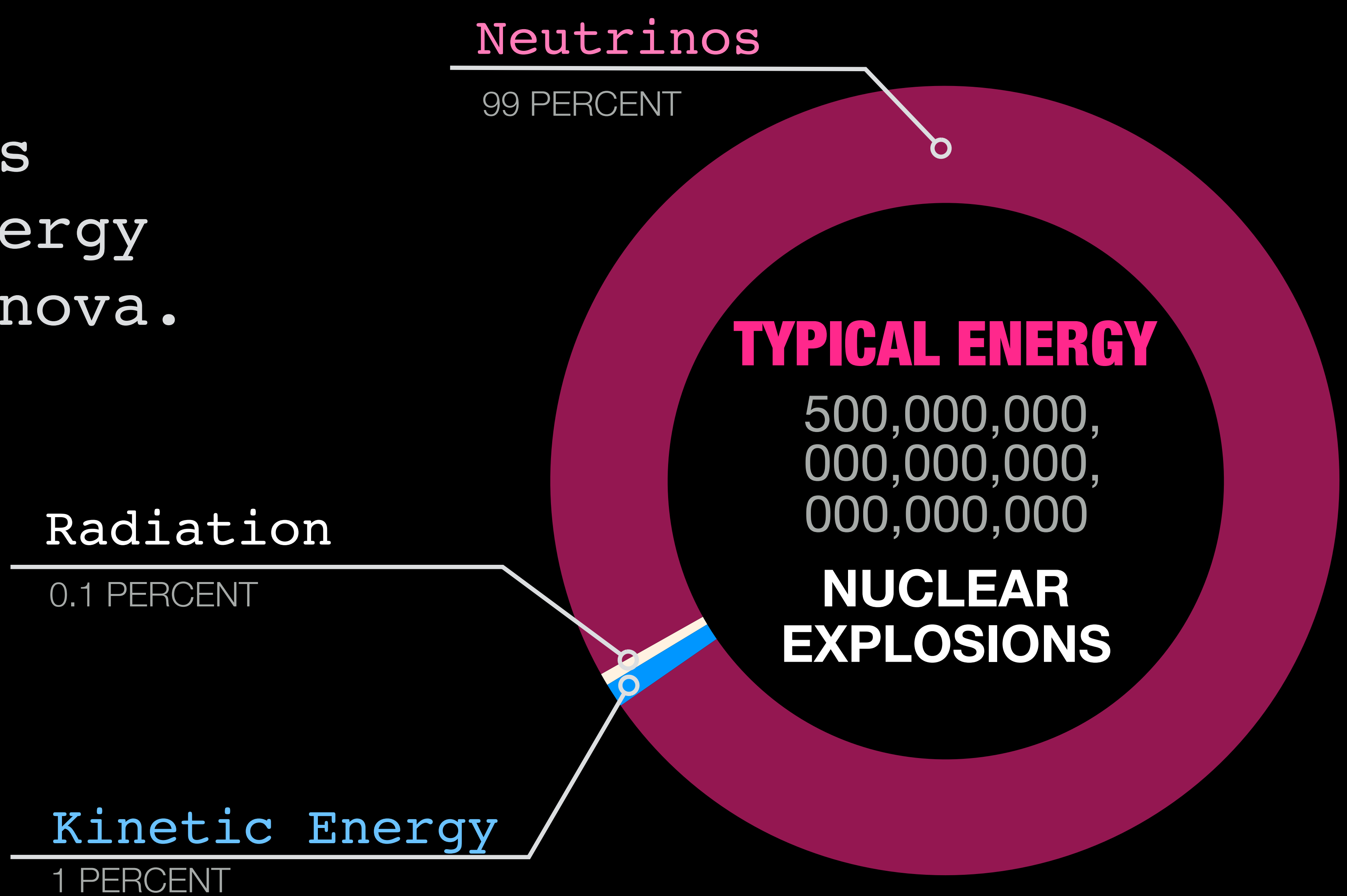


Source: NASA

Thousands of suns worth of material are ejected at enormous speeds.

Light can outshine galaxies.

But all of that is only **1%** of the energy released in supernova.



Other 99% in neutrinos!

Supernovae through history

NAME	DISTANCE (ly)	NOTABLE FEATURES
SN 185	8,200	
SN 386	14,700	
SN 393	34,000	
SN 1006	7,200	Widely observed on Earth; in apparent magnitude, the brightest stellar event in recorded history.
SN 1054	6,500	
SN 1181	8,500	
SN 1572	8,000	Tycho's Nova
SN 1604	14,000	Kepler's Star; most recent readily visible supernova within the Milky Way
Cas A (1680)	9,000	
SNR (1868)	25,000	
SN 1885A	2,400,000	First observation of an extragalactic supernova
SN 1895B	10,900,000	
SN 1937C	13,000,000	
SN 1940B	38,000,000	
SN 1961V	30,000,000	
SN 1972E	10,900,000	
SN 1983N	15,000,000	
SN 1986J	30,000,000	
SN 1987A	160,000	Archival photos of progenitor star, detection of supernova neutrinos. Most recent Local Group supernova
SN 1993J	11,000,000	
SN 1994D	50,000,000	
SN 2002bj	160,000,000	
SN 2003fg	4,000,000,000	
SN 2004dj	8,000,000	
SN 2005ap	4,700,000,000	
SN 2005gj	865,000,000	
SN 2005gl	200,000,000	
SN 2006gy	240,000,000	
SN 2007bi		
SN 2008D	88,000,000	First supernova to be observed while it exploded.
MENeaC (2009)	1,000,000,000	
SN 2011fe	21,000,000	One of the very few extragalactic supernovae visible in 50mm binoculars.
SN 2014J	11,500,000	
SN 2015L	3,800,000,000	Most luminous supernova ever observed.

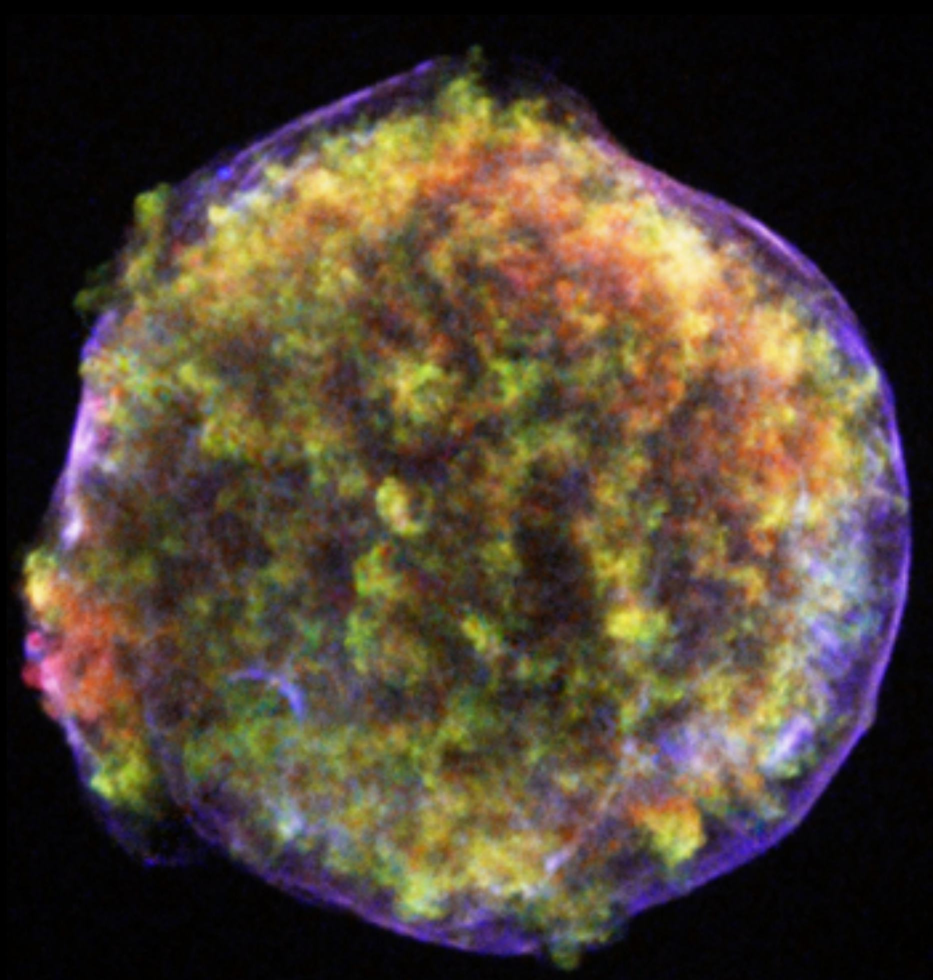
Based on this, we expect to see 1-3 per century in our galaxy.

December 7, 185 AD

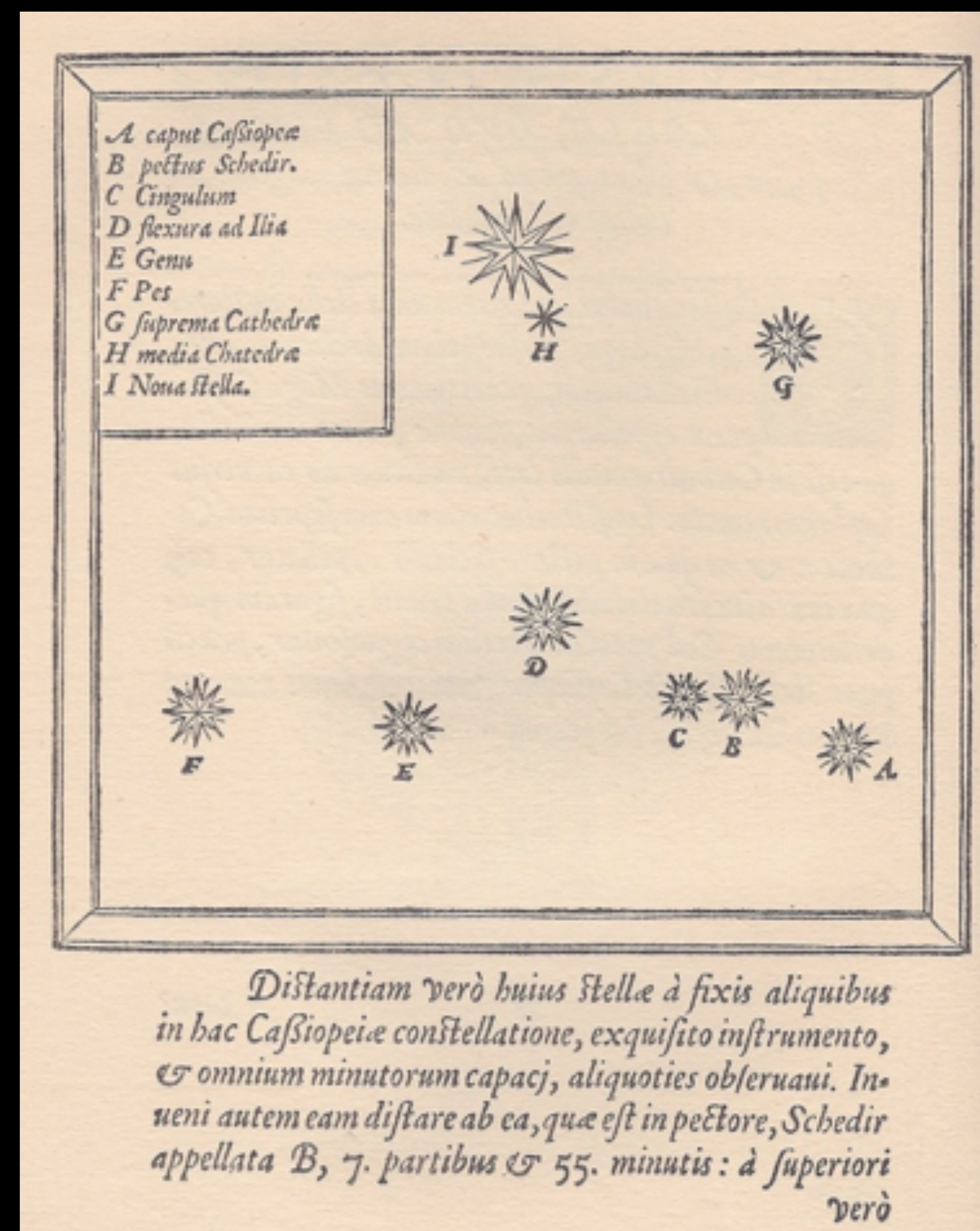
"In the 2nd year of the epoch Zhongping, the 10th moon, on the day Kwei Hae, a strange star appeared in the middle of Nan Mun, It was like a large bamboo mat. It displayed the five colors, both pleasing and otherwise. It gradually lessened. In the 6th moon of the succeeding year it disappeared."

November, 1572

Tycho's Supernova



Source: NASA

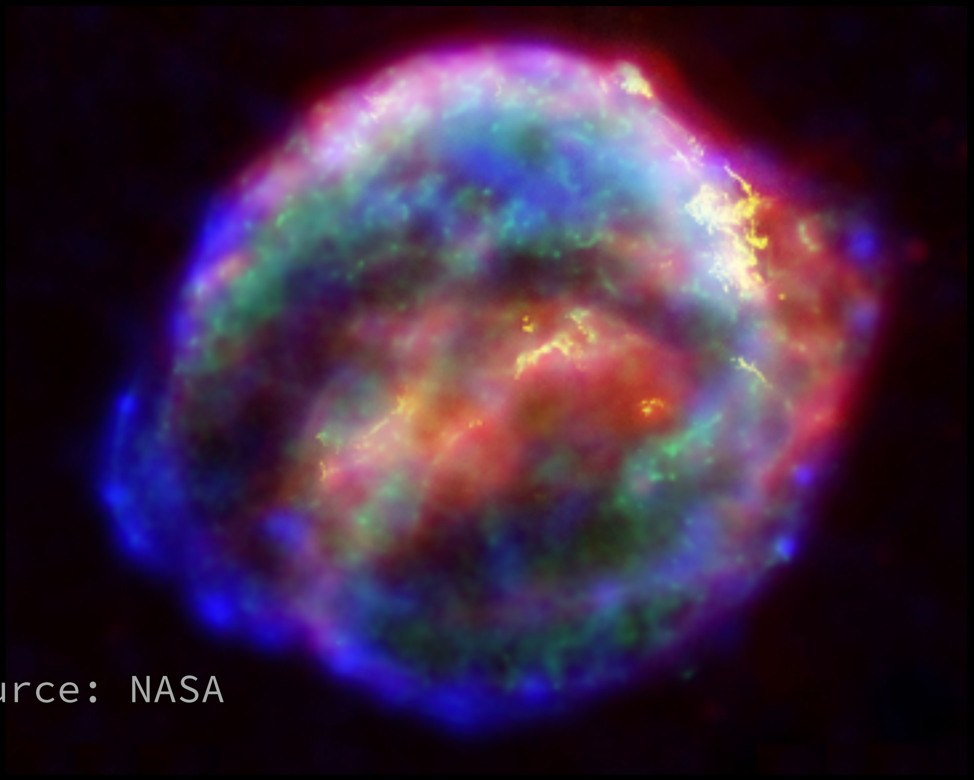


A caput Caßiopeæ
B pectus Schedir.
C Cingulum
D flexura ad Ilia
E Genu
F Pes
G ſuprema Cathedræ
H media Chatedræ
I Noua ſtella.

Distantiam verò huius ſtellæ à fixis aliquibus in hac Caßiopeiæ conſtellatione, exquiſito inſtrumento, & omnium minutorum capacj, aliquoties obſeruaui. Inueni autem eam diſtare ab ea, quæ eſt in pectore, Schedir appellata B, 7. partibus & 55. minutis: à ſuperiori verò

October 8, 1604

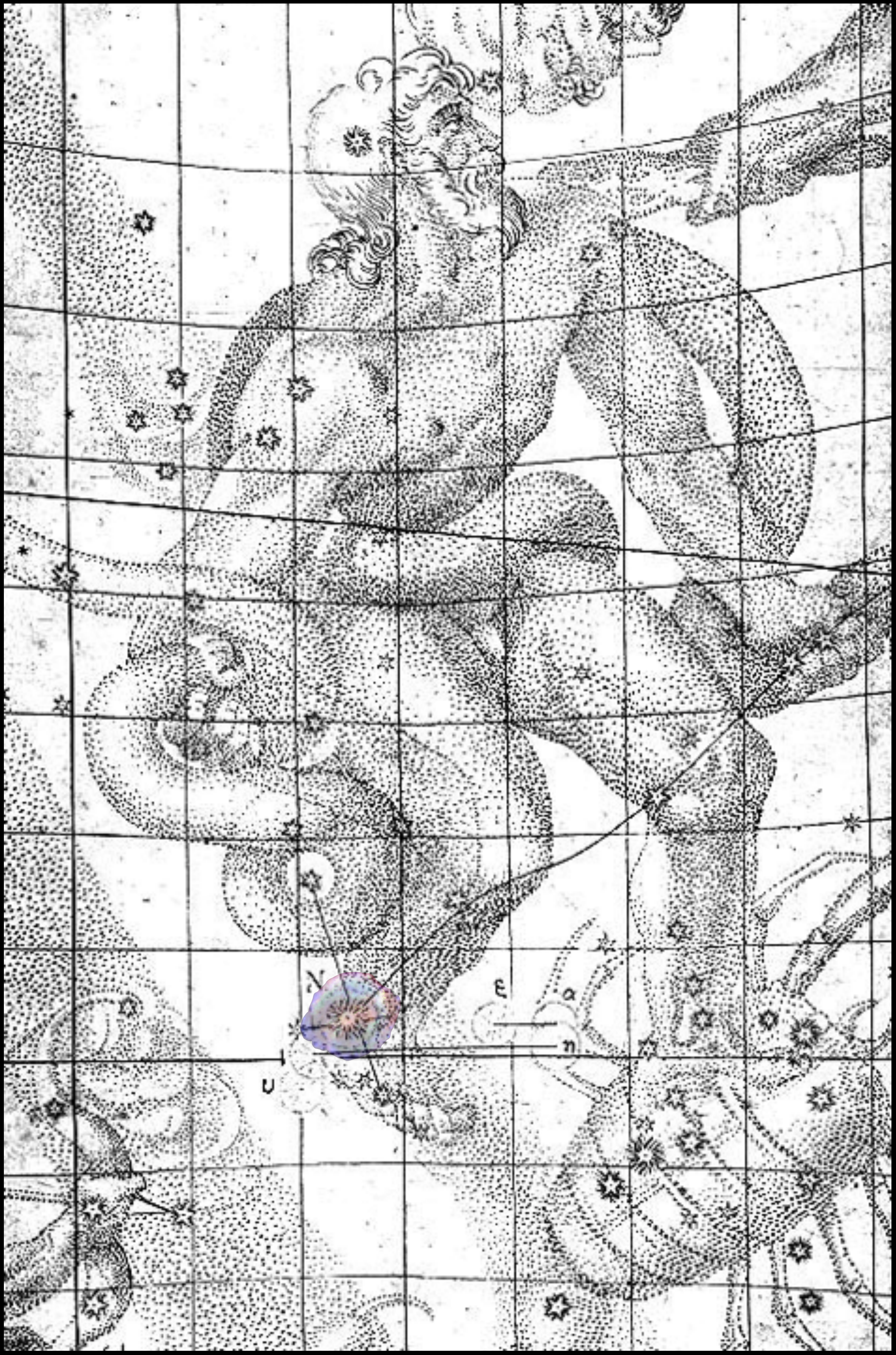
Kepler's Supernova


Source: NASA

Brighter than any star in the sky; visible during the day for 3 weeks.

Last-seen SN unquestionably seen by naked eye.

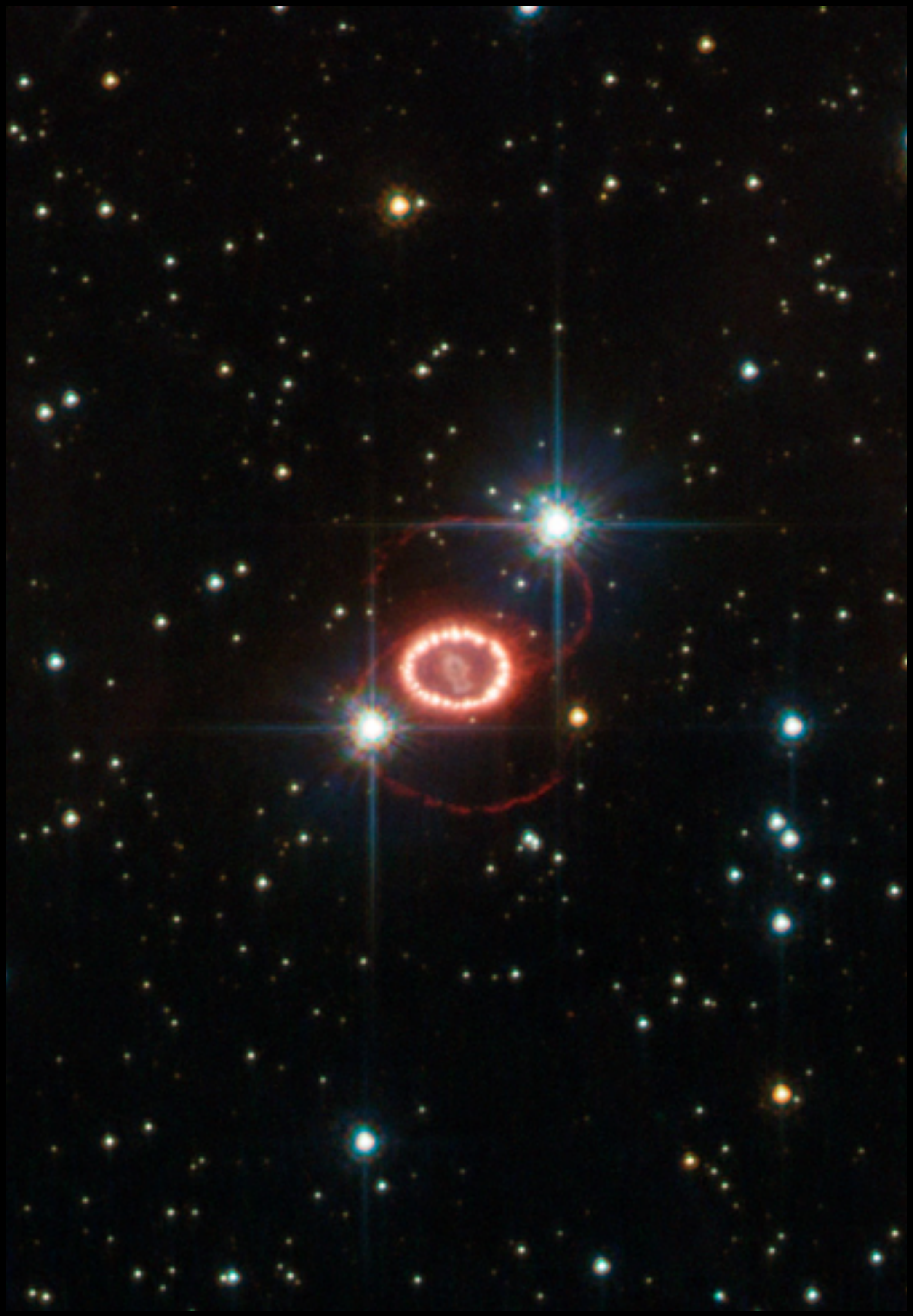
Before invention of telescope.



February 24, 1987

SN 1987a

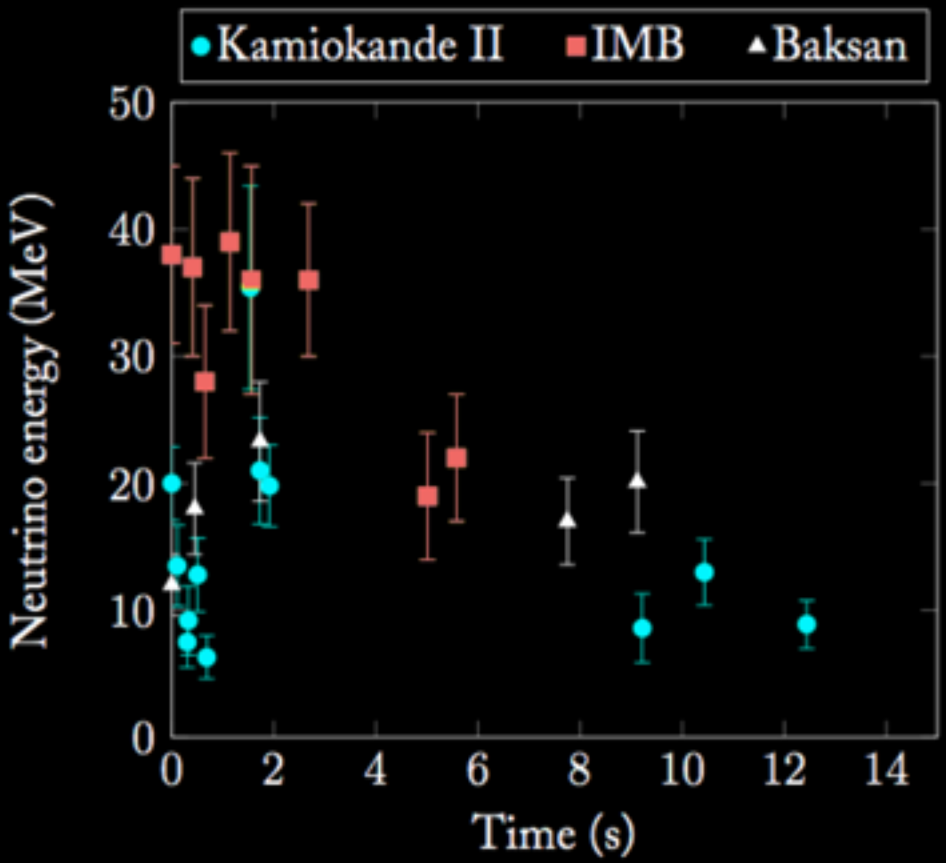
First nearby SN since the invention of the telescope.



Source: NASA

Luckily that technology was well-developed by then; we already had space telescopes.

Were able to watch ejecta evolve over time

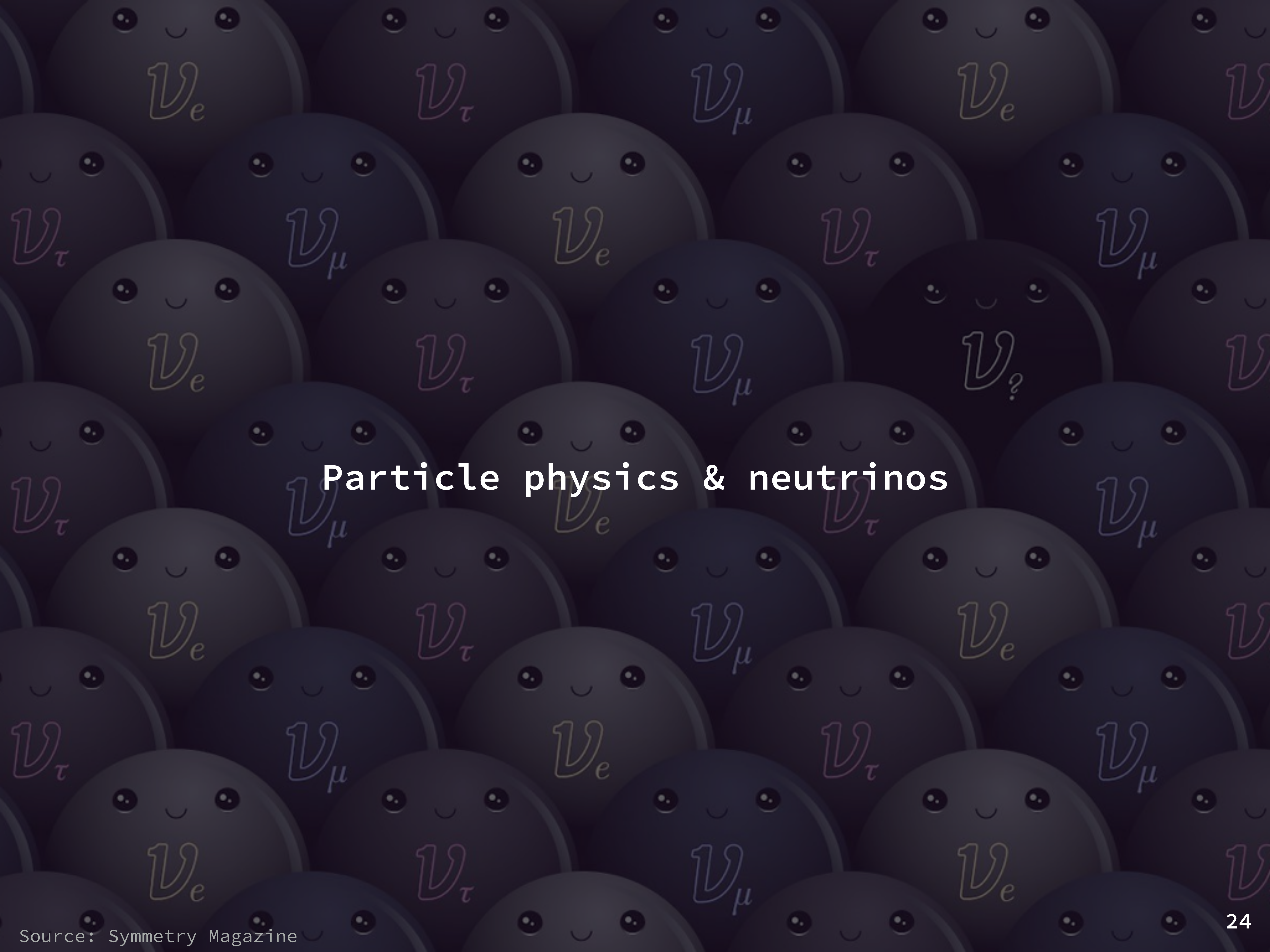


First observation of neutrinos from SN

Birth of neutrino astronomy

Source: NASA

Particle physics & neutrinos



Source: Symmetry Magazine

Particle physics in a nutshell

- *What are the building blocks of the Universe?*
- *How do they fit together?*

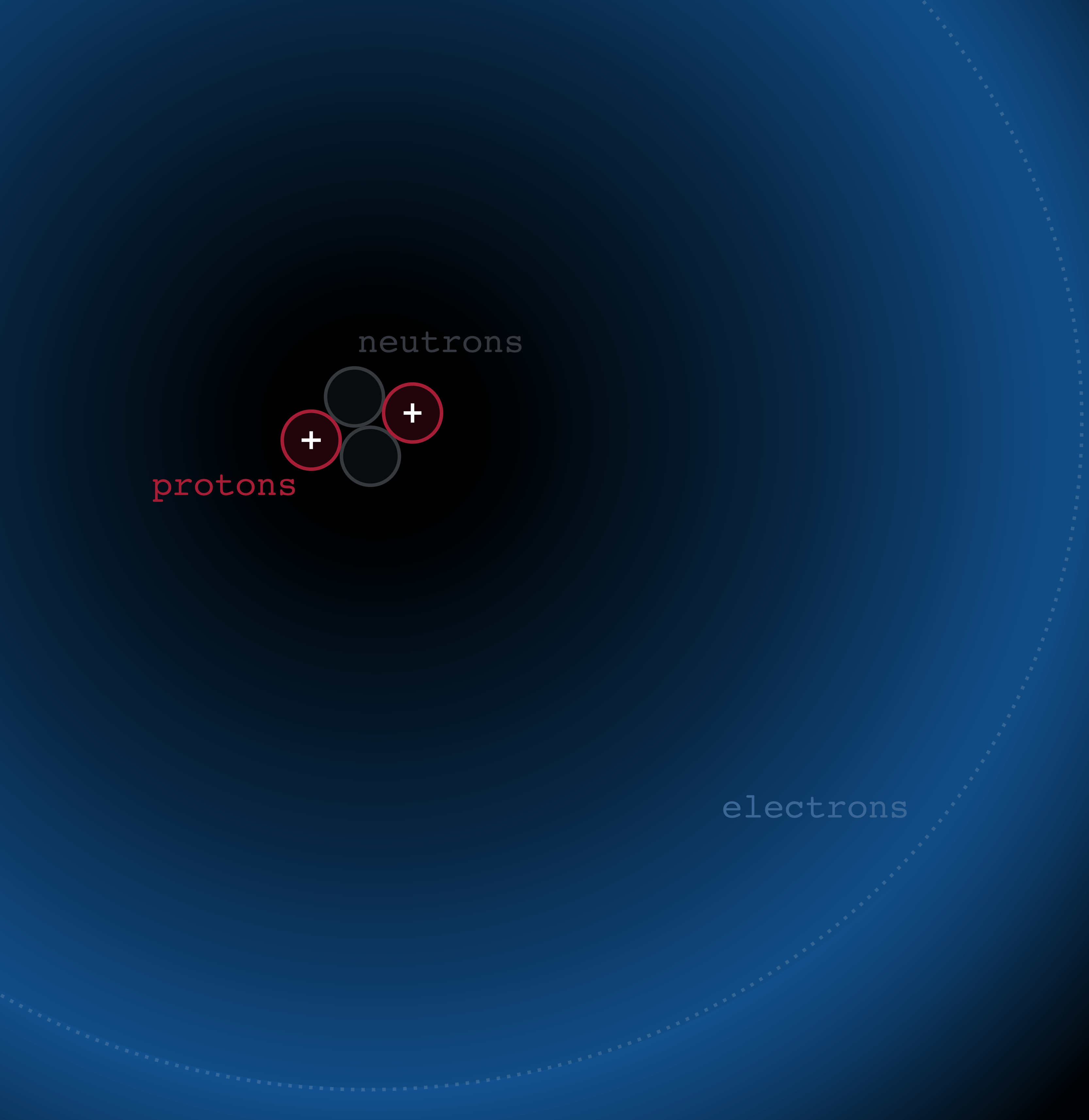
Elementary *(fundamental)* **particle:**

"Any particle which is not made up of other particles."

— Justin Vasel, 8 January 2016

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
	*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
	**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

- Alkali
- Alkaline
- Transition
- Lanthanoid
- Actinoid
- Poor
- Metalloid
- Nonmetal
- Halogen
- Noble gas
- Unknown



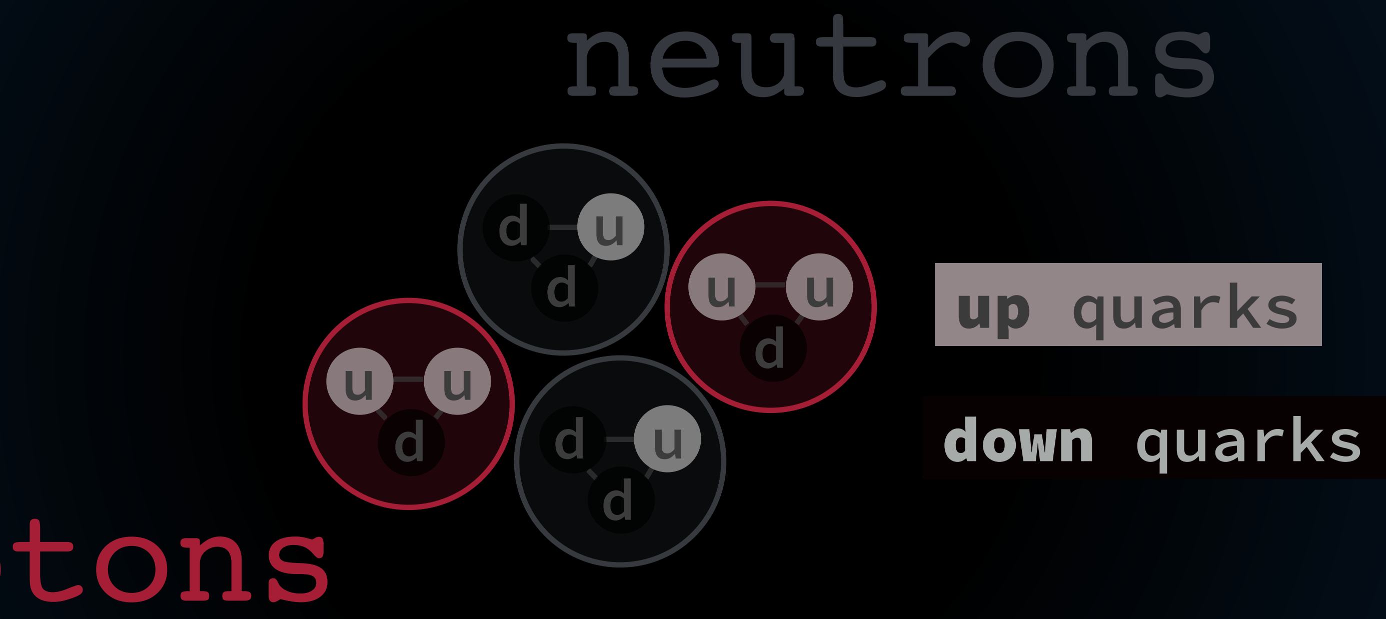
The atom

The name means "indivisible"

Turns out they're not.

Comprised of a nucleus (protons and neutrons) and electrons.

But are ***those*** indivisible?



The electrons are indivisible

Protons and neutrons are not; they are made of quarks

The quarks, however, are indivisible.

These particles constitute the fundamental building blocks of atoms, but they are not the only particles...

electrons

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen these neutrons much earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr. Debye, who told me recently in Bruxelles: "Oh, It's well better not to think about this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tübingen personally since I am indispensable here in Zürich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

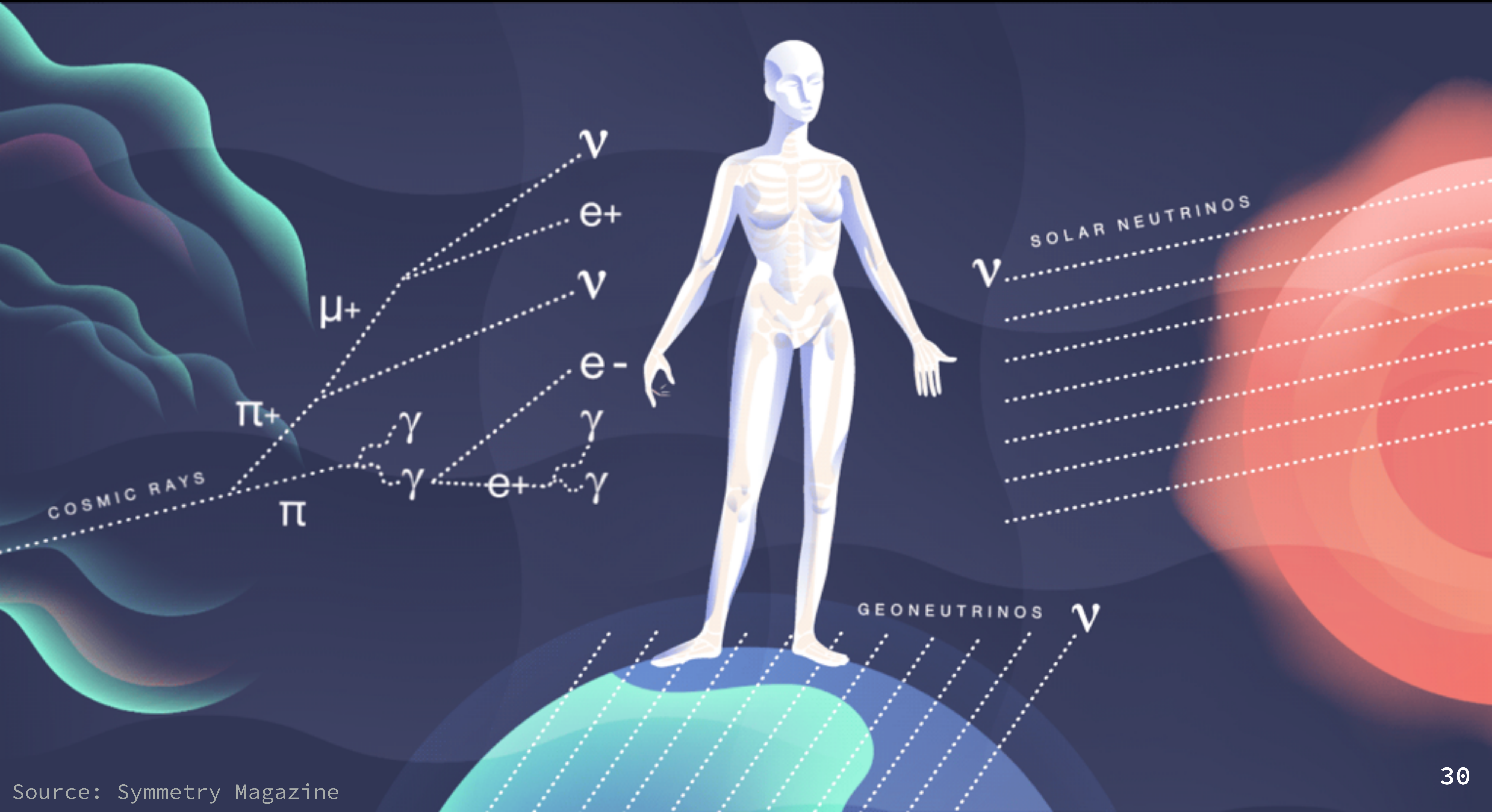
Your humble servant,

W. Pauli

Neutrinos are everywhere

They come from many sources; second most common particle in Universe.

100 trillion of them pass through your body every second.

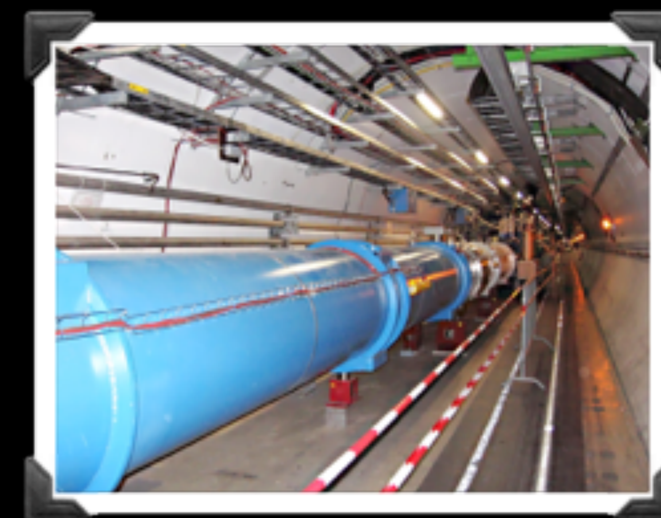


Source: Symmetry Magazine

The Standard Model

Describes the fundamental particles of the Universe and how they interact with one another.

Successful, but always being tested (at CERN, Fermilab, etc.)



LHC at CERN

Particle classes:

Quarks **Bosons**

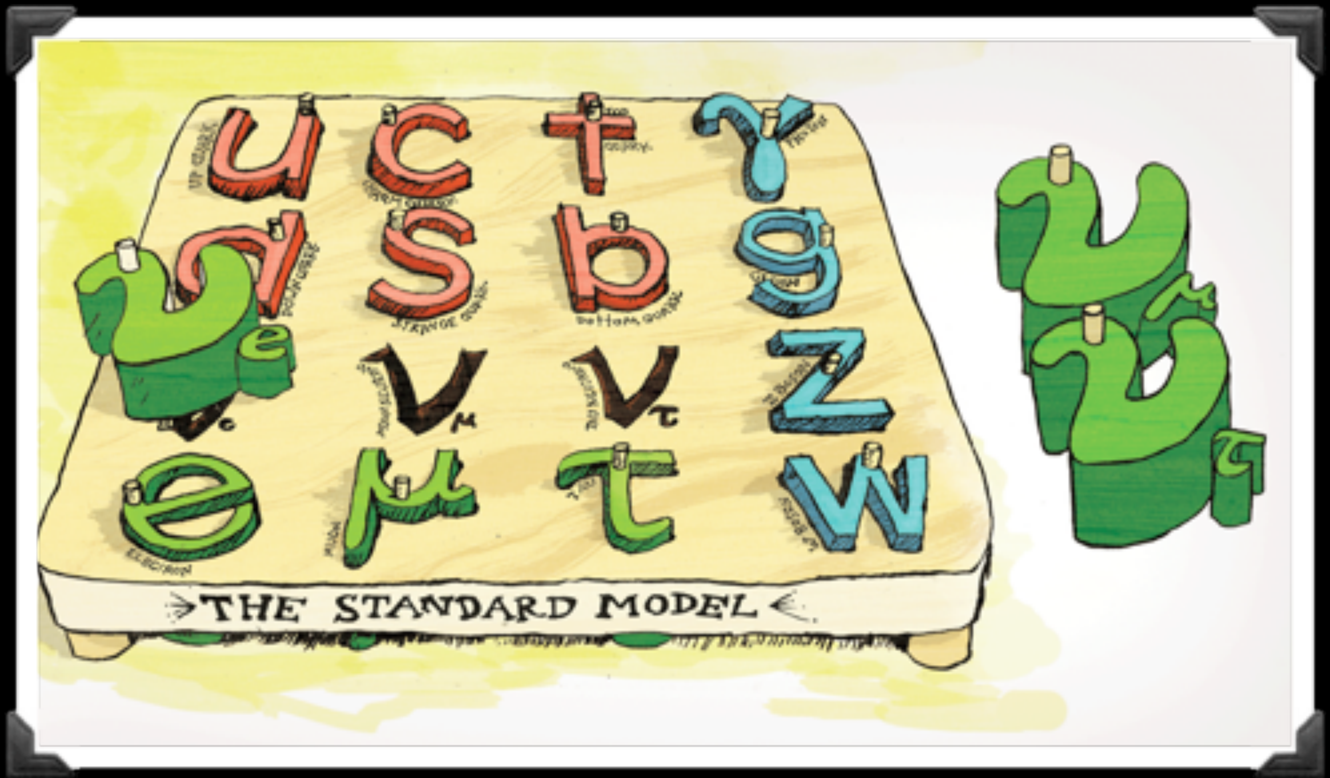
Charged leptons

Neutrinos

Outstanding questions:

- What gives rise to the Standard Model of particle physics?
- Why do particle masses and coupling constants have the values that we measure?
- Why are there three generations of particles?
- Why is there more matter than antimatter in the universe?
- Where does Dark Matter fit into the model? Is it even a new particle?

Taken from *Wikipedia*



Source: Symmetry Magazine

Standard Model Problems

- Does not explain gravity
- Getting messy, involves lots of constants; lacking elegance in this sense.
- Does not explain neutrino masses.
- No clear explanation for dark matter/energy, ultra high-energy cosmic rays.

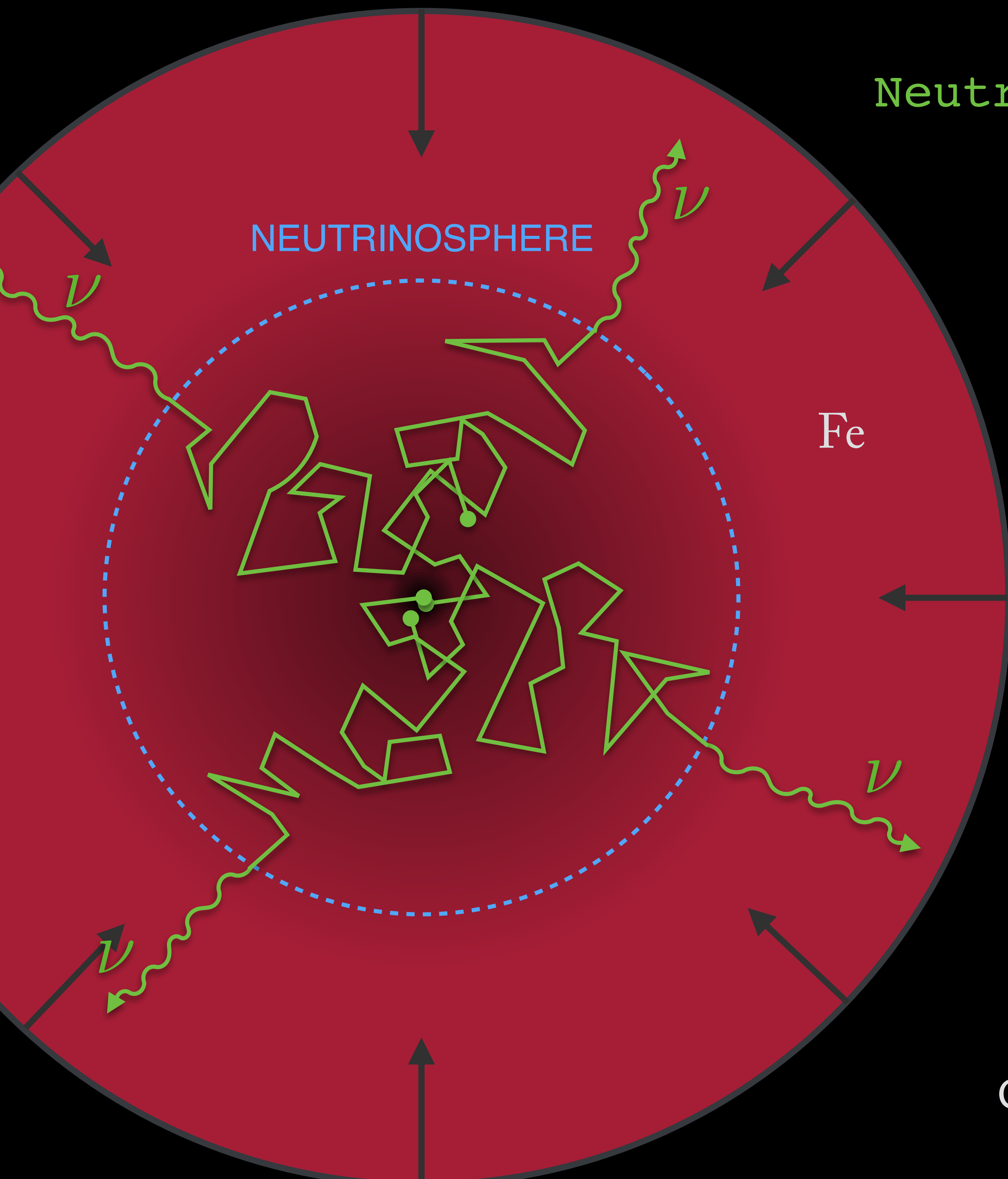
Neutrinos don't quite fit into the SM like the rest of the fundamental particles do; they're bigger than they "should" be.

These discrepancies lead to a field of study known as "Beyond the Standard Model (BSM)" physics.

As we further investigate these particles, we hope to solve some of these perplexing questions.

Putting it all together

Source: Symmetry Magazine



Things get very dense, very fast.
Neutrino diffusion time > collapse time

Neutrinos get **trapped**.

Boundary between neutrino-opaque and neutrino-transparent regions is the *neutrinosphere*.

Can't recreate these conditions in a lab. Only a collapsing stellar core can trap neutrinos this way.

Collapse takes ~350 milliseconds.
Core shrinks from 3,000 km to 30 km in that time.

At nuclear densities, the iron core stops compressing, and the inflating matter rebounds off of it.

1. Once the core “bounces”, a shock wave develops.

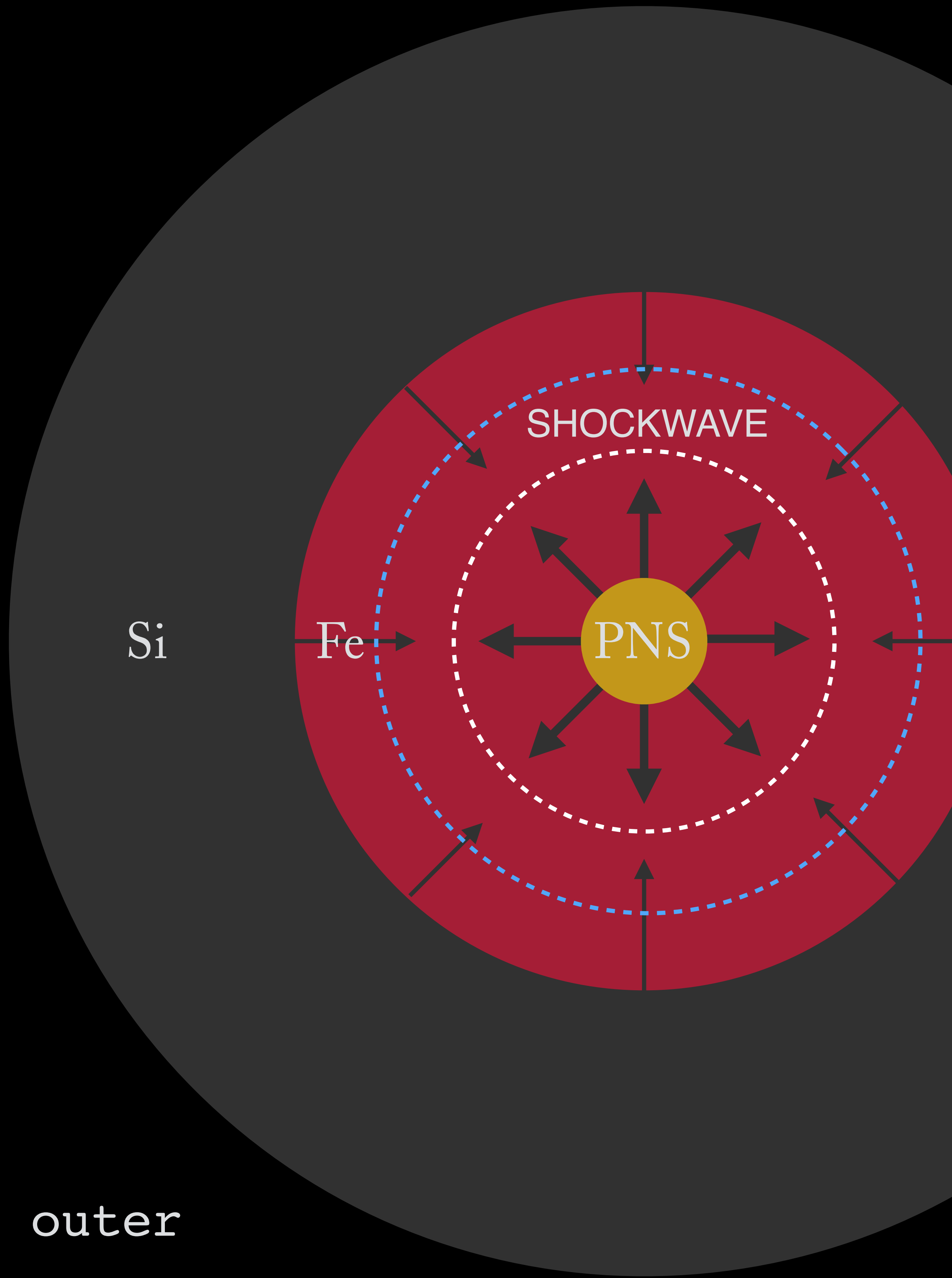
2. Shock front dissociates heavy nuclei, looses energy in process.

3. Shock front stalls.

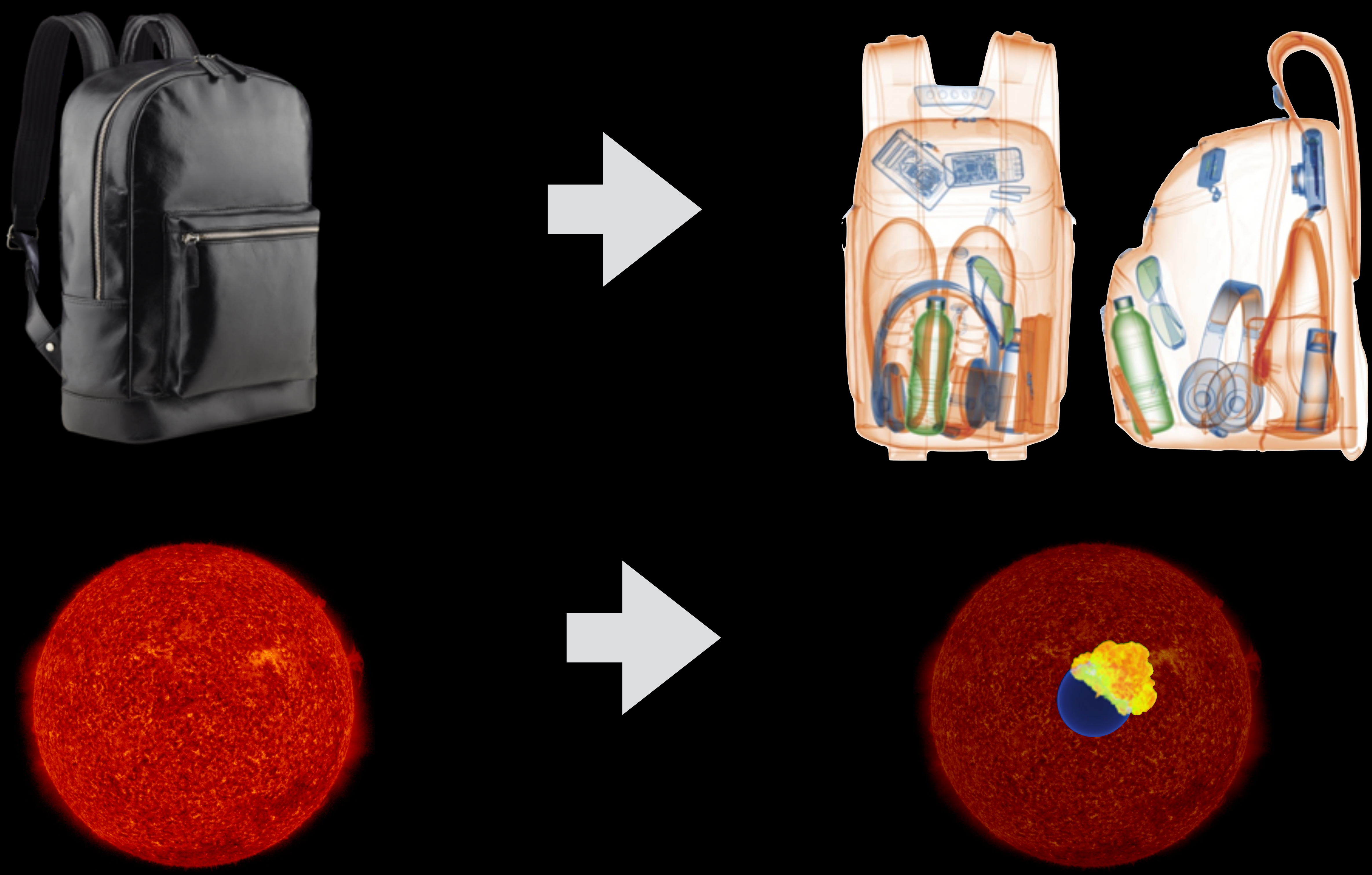
4. Neutrino-heating is needed to keep the shock from stalling and falling back onto Proto-Neutron Star (PNS).
   Delayed explosion mechanism

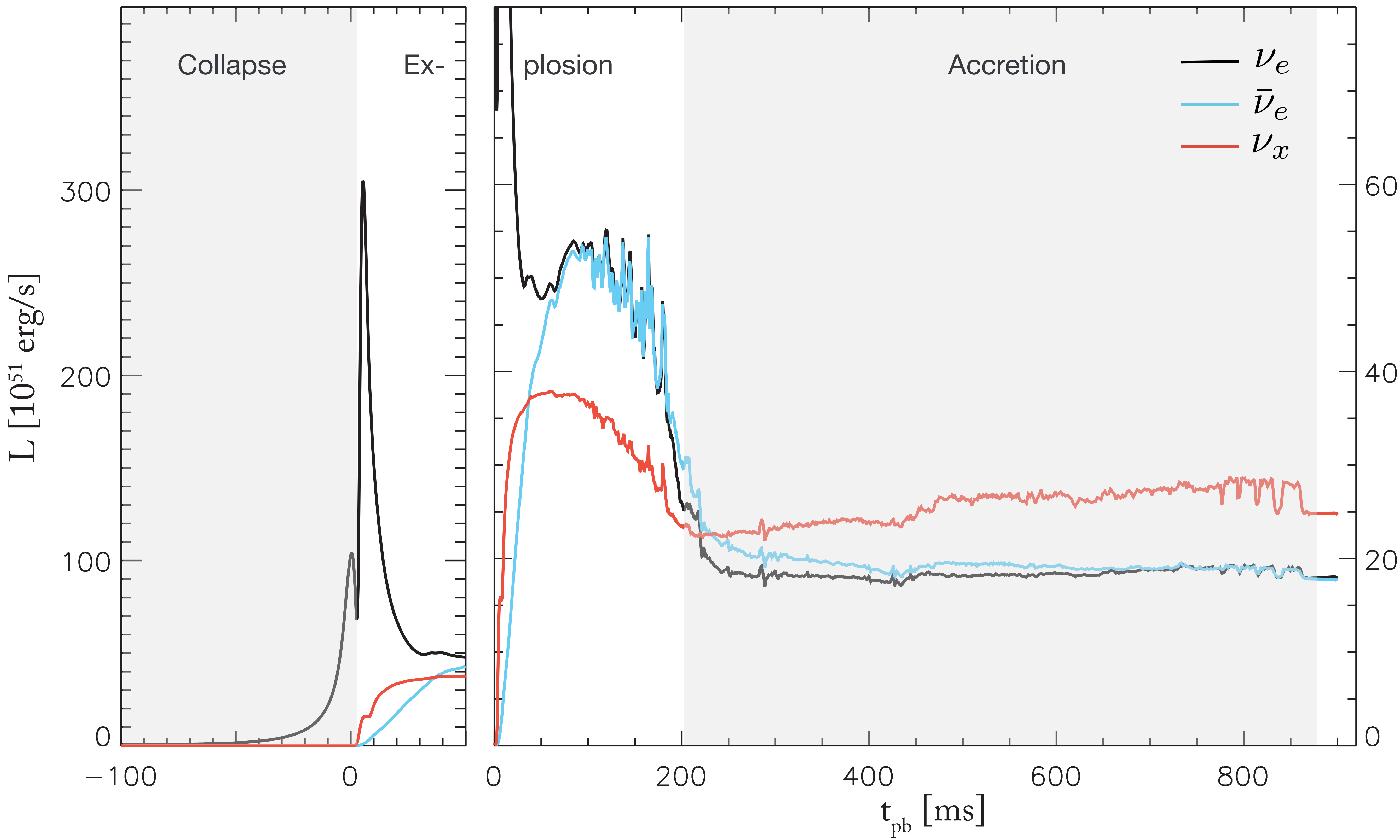
5. Shock front reaches neutrinosphere; neutrinos are immediately released.
   Prompt burst

6. Once shock front leaves iron core, outer layers are no obstacle; explosion proceeds.



Neutrinos let us see inside the stellar core



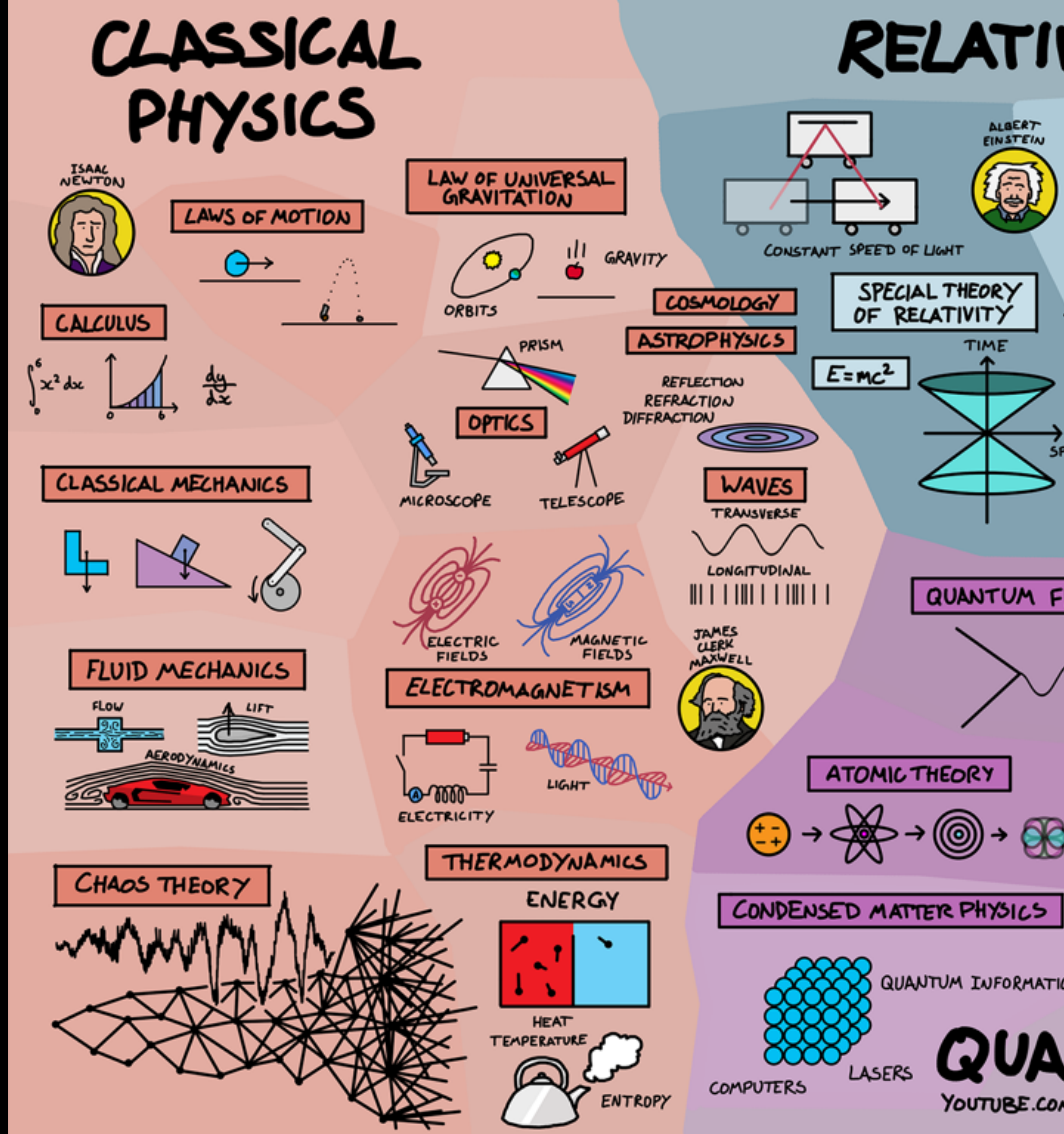


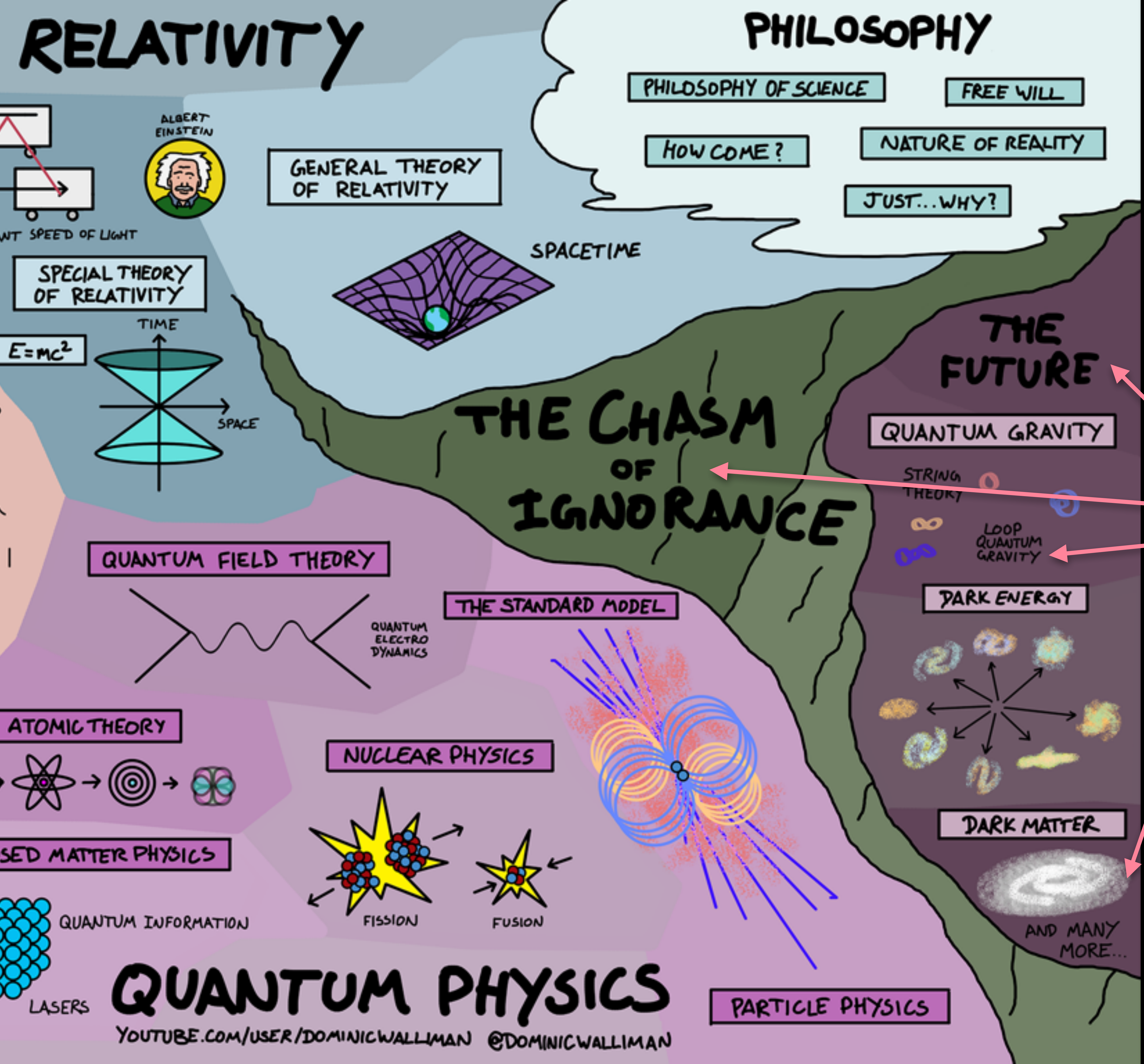
Expected SN neutrino signal over time. Can distinguish stages of the explosion process.

Supernovae incorporate ***almost every*** subfield of physics.

This makes them great labs for understanding lots of phenomena.

But first we need to see one!





Here be dragons

SN 1987a

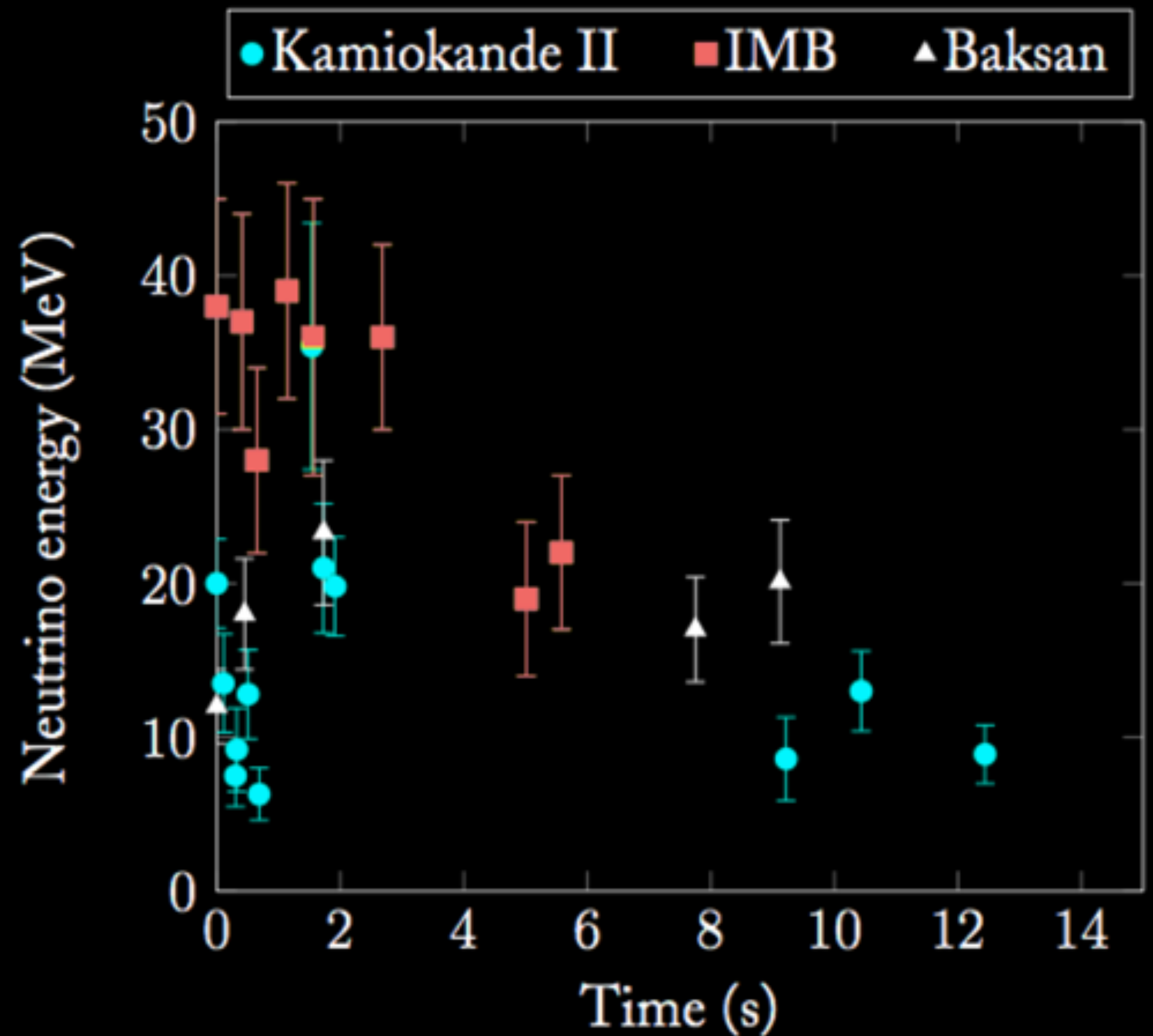
25 neutrinos detected by three experiments.

Arrived 2-3 hours before light from explosion.

Measurement of the neutrino energy over time tells us details about the progenitor star and about neutrinos.

Set a mass limit on the neutrino (m < 16 eV)

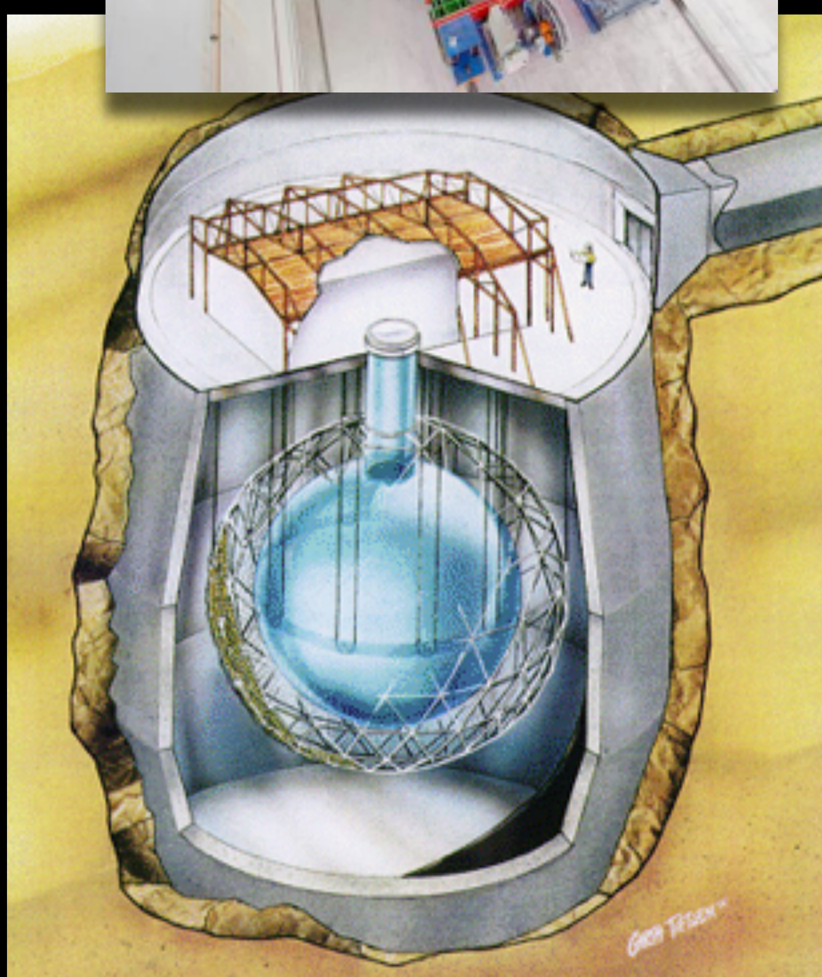
Other limits could be placed on the neutrino charge and the number of possible neutrino flavors.



Thousands of papers have been published on these data since 1987.

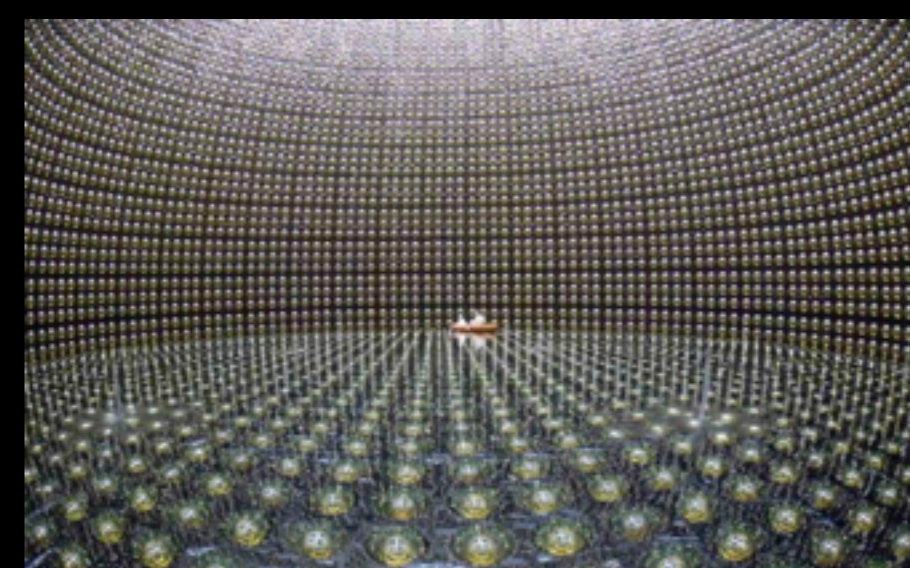
With only 25 neutrinos!

Current/future detectors

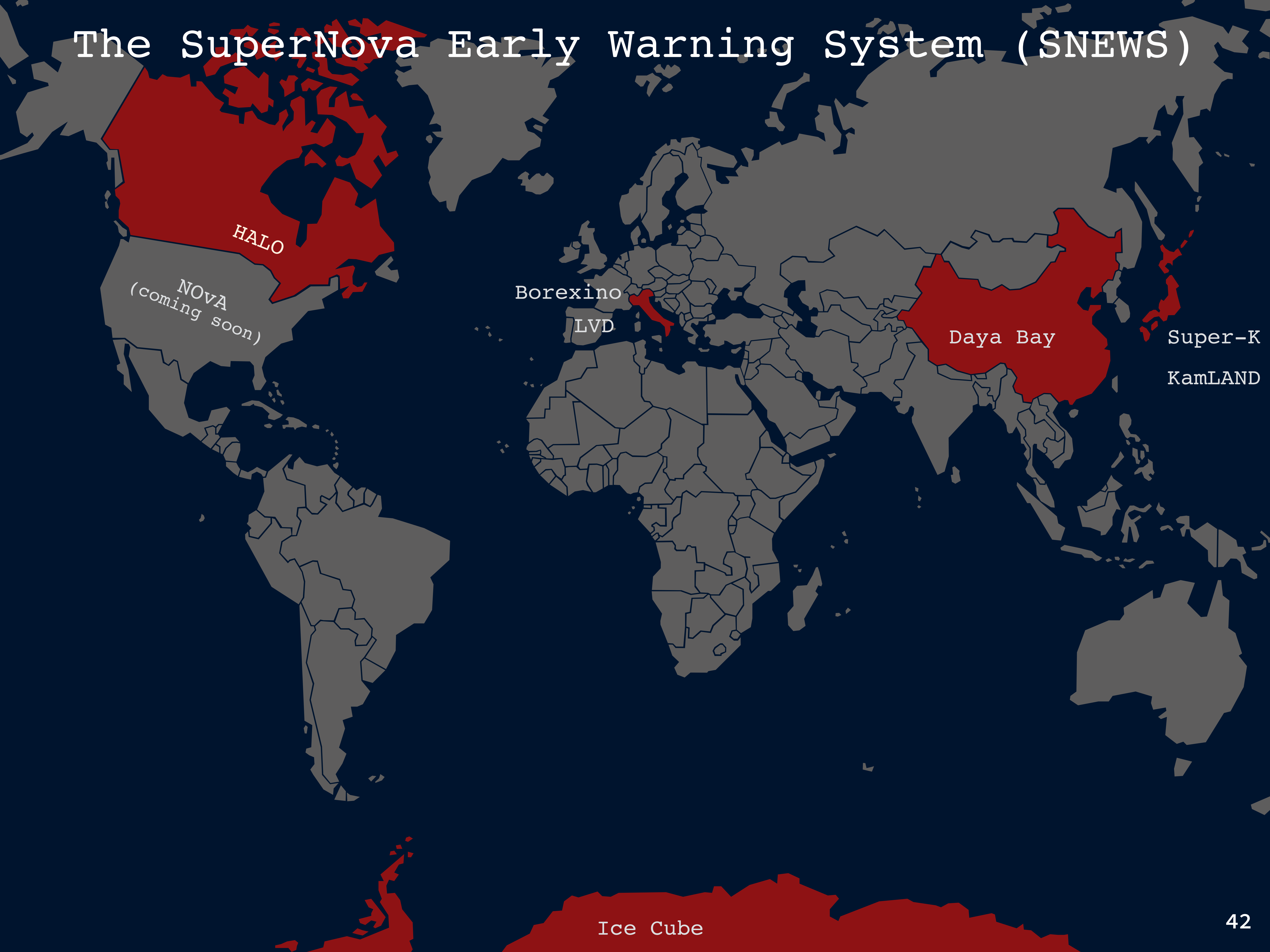


	Livermore	GVKM
LVD	319	190
KamLAND	318	189
SNO+	237	141
Borexino	71	43
Daya Bay	79	47
Double Chooz	18	11
RENO	29	17
NOνA far	6811	4057
NOνA near	32	19
MiniBooNE	161	96

Expected number of neutrinos by today's detectors for a supernova 10kpc away.
We'll see thousands next time.



The SuperNova Early Warning System (SNEWS)



Neutrino detectors, ***ASSEMBLE!***

Now we wait...

The neutrinos from the next galactic SN are already on their way.

The SN/Neutrino community is ready to spot them when they arrive; study the explosion as it unfolds.

We will see thousands of neutrinos, rather than the 25 from SN1987a.

Will lead to much better understanding of neutrinos and supernovae.

Are we there yet?

Want to learn more?

Many resources online.
Google "supernova neutrinos"

Check out the SNEWS website. You can even sign up for alerts and be the first to know when the next SN happens!
http://snews.bnl.gov

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THANK YOU FOR YOUR TIME AND ATTENTION!